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SOLID LUBRICANTS FOR SPACE STRUCTURES

SBIR Final Report : PHASE II

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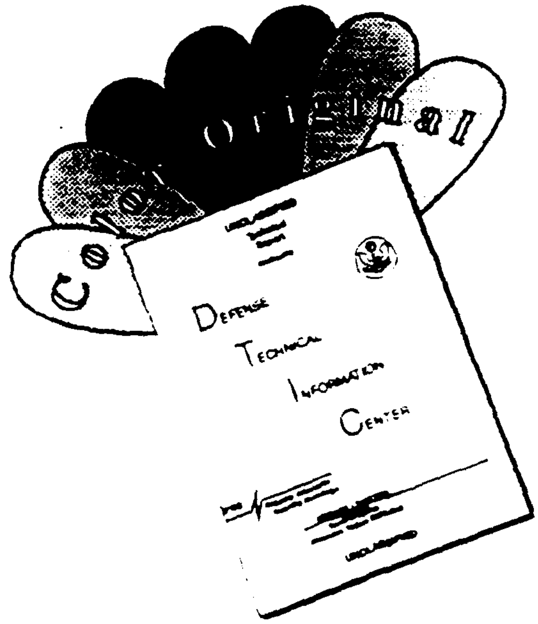

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In this Phase II effort, copper-lead alloys of three different compositions (90-10, 75/25, and 50/50 copper-lead) were processed by swirl die continuous casting in the form of ingots and further processed into powders using the gas atomization method. The powders were compacted using shock compaction and hot isostatic pressing. Friction and wear studies revealed that the 75/25 alloys had the best friction and wear rates under a range of sliding speeds and contact loads. Bearing cages, brushes, bushings and gears were produced from the different compositions and processing conditions. The components were tested in specially designed test rigs by the National Council for Tribology, U.K.. The 90/10 hot isostatically pressed bearing cages outperformed the currently used lead-bronze cages and produced minimum noise for One (1) million revolutions. In the case of brushes, all the compositions and processing conditions outperformed all the materials that had been tested previously at NCT. Moderate to little improvements were observed in gears and bushings.

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1. INTRODUCTION

Numerous platforms will be deployed that will be used to target and retarget enemy locations/defense systems using stationary or moving laser weapons. These systems will utilize mechanically interlocked hardware (caged bearings or bearings for ultra precision gimbals pointing mechanisms) controlled through precision electronic devices. This creates a need for reliable and repeatable efficiency and accuracy of these defense systems for extended periods of operation in space. Components such as rail guns are specifically expected to be subjected to repeated friction during defense maneuvers. Lubrication of these moving mechanical assemblies will hence be a critical straw in the overall system.

Liquid phase lubricants that are commonly used in earth conditions (often petroleum based) cannot be used readily in space as many of these materials contain organic constituents that degrade or change properties with time and temperature. Several of these fluids may also volatilize, migrate, or boil away either directly to space or contaminate the space structure unless the lubricant were of low vapor pressure and/or suitably sealed to prevent molecular effusion. While temperatures within spacecraft or space platforms can be controlled by various means, components or structures exposed to the atmosphere (solar arrays, hinges for lifting arms for hatches, antenna drives etc) will be subjected to temperatures ranging from - 40°C to + 80°C depending on the orientation of the space platform/structure to the sun, eclipse durations, etc. This variation in temperature poses a major problem for the use of oil or grease, as the lubricants will become viscous when it is cold and show large changes in viscosity when hot such that the hydrodynamic film will be ineffective. Further, extended service of some of these components in the degradation prone environment where atomic oxygen plays a major role in the performance of lubricants limits the use of conventional materials. Thus, the choice of any coating or lubricant material for service

under these severe conditions must be based on avoiding frequent replacements and ensuring long term service.

Solid lubricants are materials that can provide lubrication to two relatively moving surfaces under essentially dry conditions. Over the years, many different types of dry lubricants have been used and are classified as either bonded or unbonded. Most of the technical literature on solid lubricants is relatively recent (last 50 years), however the knowledge that graphite and MoS_2 were solid lubricants has existed for a much longer time.

In space environments where oxygen and water vapor are not readily available to repair damaged surfaces, the performance of solid lubricants will be an important factor in determining the efficiency of several operating systems. Mechanisms for use in space and vacuum environments generally have a requirement for long term durability with no maintenance during their life. In addition low friction or torque levels with low frictional noise are often desirable and furthermore over the life duration there should be minimal wear debris production.

Solid lubrication can be achieved either by coating tribological components with a lubricant or alternatively directly manufacturing them from a self-lubricating material. In addition the life of coated components can sometimes be enhanced by the fitting of a self lubricating element which regenerates the film by a transfer process; for example lead ion plated bearings in which a lead bronze cage replenishes the dry lubricant on the bearing races.

A comprehensive handbook for lubrication in space was assembled by NASA in 1985 [1]. This handbook serves as a useful guideline for providing all the data associated with the different types of lubricants that are currently <u>commercially</u> available in the form of bonded or unbonded films. The development of strategic defense systems that are going to experience extremely different service conditions coupled with extended and sometimes demanding performance has motivated the need to develop techniques for producing solid lubricant alloys. Several methods and techniques

that have been developed and commercialized to produce composites and non equilibrium alloys can now be adapted for the development and commercialization of products for use as solid lubricants in space and earth related applications.

Prior solid lubricant studies [2-3] have been empirical and little attempts have been made by researchers to understand the concept of using different types of soft metals as solid lubricants. A number of investigations were focussed on the use of inorganic compounds as solid lubricants [4]. Some of the materials studied include:

- organics (soaps, fats, waxes),
- polymers (PTFE, polyethylene, methacrylate, polyimides),
- inorganic compounds (sulfides, chlorides, iodides, oxides, hydroxides), and,
- glasses (boric oxide, silicates and phosphates).

Some of the important properties desired in a solid lubricant are:

- lubricant film adhesion,
- film cohesion,
- crystal structure,
- shear strength,
- presence or absence of absorbed species,
- presence of film impurities, and,
- the composition and finish of the substrate material.

Other materials that have been studied include double oxides, dichalcogenides, mixed fluorides, and intercalcated layer lattice compounds that have a hexagonal layered crystal structure. Some of the most common compounds of this type are MoS_2 and WS_2 whose stabilities are limited by the temperature and atmosphere.

Solid lubricants offer several advantages compared to conventional synthetic lubricants. Some of these include:

- their ability to be used under high load conditions,
- suitability for use over a wide temperature range,
- resistant to the effects of nuclear and gamma radiation, and,
- excellent storage stability.

The disadvantage of these solid lubricants are:

- they are generally more expensive,
- provisions for the removal of wear debris must be provided,
- higher friction coefficients than with hydrodynamic lubrication, and,
- poor elevated temperature properties.

1.1 Characteristics of Solid Lubricants

Solid lubricants generally exhibit low shear strengths and hence low friction. Crystalline lubricants undergo shear by slipping on preferred crystallographic planes. Slipping leads to a severe plastic flow such that the solid lubricant particles adhere to the surface as a continuous film. Further, since the particles in the lubricant film are soft, they undergo very low abrasion. Most solid lubricants are also thermochemically stable and hence can be used in a wide variety of environments without problems related to corrosion.

A limited number of soft metals can be used as solid lubricants (see Table 1) [5]. Soft metals have:

- low shear strengths,
- can be applied as continuous films over hard materials,
- good conductors of heat and electricity, and,
- stable at elevated temperatures as well as in vacuum.

TABLE 1 Properties of Soft Metals

Metal	MOH Hardness	Melting Point (°C)
Indium	1	156
Thallium	1.2	1552
Lead	1.5	328
Tin	1.8	232
Cadmium	2	321
Barium	--	729
Silver	2.5 - 3.0	961
Gold	2.5	1063
Platinum	4.3	1769
Rhodium	4.5 - 5.0	1966

Coefficients of friction for thin films of soft metals on hard substrates are typically of the order of 0.30.

Soft metals can be sputtered or ion plated on to a surface. Sputtered coatings are thin and usually of the order of 2000-5000°A thickness. Of all these materials, gold demonstrates the best resistance to oxidation, however; the prohibitive cost of this material prevents its economical use in the large number of bearings, sleeves, bushings or other moving components in space structures. Indium, silver and tin offer reasonable oxidation resistance through the formation of oxides, however; their cost is still not within the range desired for mass consumption. The cheapest material that can be used in large quantities as a solid lubricant is lead and this is accompanied by the superior load transfer and low shear strength characteristics of the metal. This material can also be combined with other metals such as copper or aluminum so that strength, conductivity and corrosion resistance can be enhanced.

Lead films have been used previously in research investigations [6-7]. In these studies, films were plated, implanted

or sputtered on to the surface. One major limitation that has hindered the use of lead is the difficulty associated with the plating process. Lead cannot be plated easily on many substrate materials and the process has to be controlled carefully such that minimum formation of undesirable compounds of lead (mostly different stoichiometries of oxides) are generated on the surface. These compounds can be destroyed easily under loads. On the other hand, sputtering or implantation techniques are effective but expensive and are limited to small surfaces and to minimal thicknesses of penetration (typically 250 microns). Use of soft metals in several friction applications would be benefitted if a composite/alloy was created such that it would have alternate islands of lubricant and a heat dissipating load bearing material. A **reservoir of lubrication** would also be created and this could be useful in carefully tailored combinations of alloys containing the soft metal such that specific friction values can be attained for a given application and also provide the benefit of **extended life.**

1.2 Processing of Composites for use as Solid Lubricants.

Copper due to its excellent thermal conductivity, affordable price and ability to withstand moderate mechanical strengths is a candidate for numerous applications involving solid lubrication. Alloys of lead containing copper are often difficult to produce as the two metals are immiscible. Although lead mixes with several metals in the liquid state, immiscibility or the monotectic reaction at the lower temperatures leads to segregation upon solidification. The phase diagram for the copper-lead system is shown in Figure 1 [8]. Monotectic reaction results when Liquid 1 $\rightarrow$ Solid 1 + Liquid 2. The Liquid 2 then subsequently solidifies at a lower temperature to Solid 1 + Solid 2. This secondary reaction creates segregation during the transition from the liquid to the solid state creating several phases that are rich or poor in lead. Such phases are observed when the concentration of lead exceeds 36% in copper-lead mixtures.

Cooling rate influences the mechanism of segregation and the solidification process in the Cu-Pb alloy system. Limited attempts [9-11] have been undertaken to study the influence of the rate of cooling on the solidification process. In most of these studies, the resulting microstructures obtained have varied from extremely lead rich islands to those that were almost completely copper.

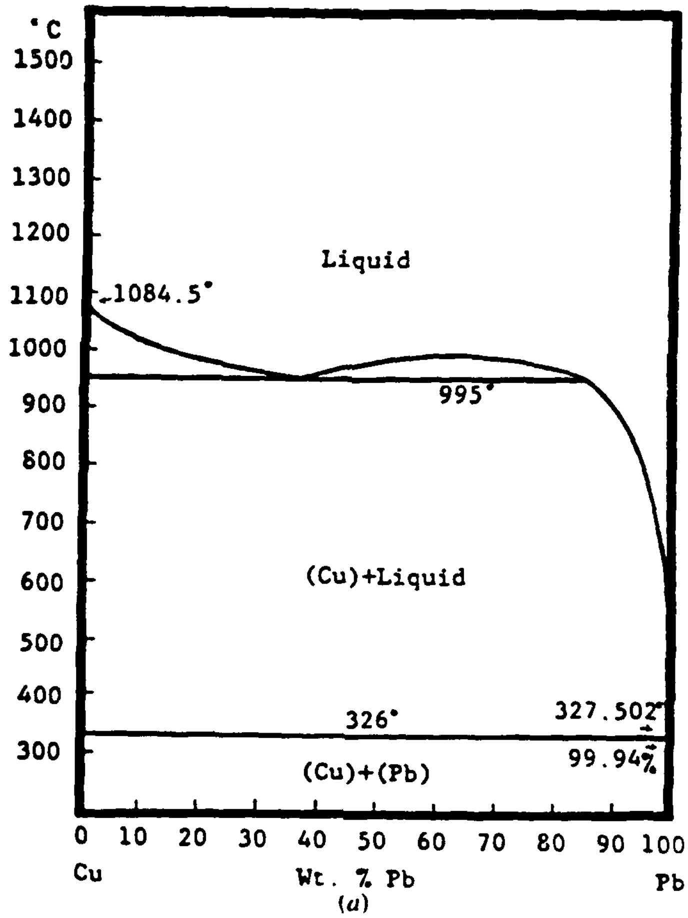


FIGURE 1 Phase diagram for the copper-lead system

In all these studies, the mechanisms associated with segregation have been outlined. Other investigators [12-16] have attempted to remove the immiscibility by producing lab scale quantities of these alloys in microgravity environments using a KC-135 aircraft and comparing these with alloys produced in gravity. Segregation of lead to either the top or bottom of the test ingot based on the rate of extraction of the heat continued to be a problem under conditions of microgravity. In some cases, the addition of aluminum appeared to show limited possibilities for homogenization of the microstructure in the microgravity environment. For the specific copper-lead system investigated by other researchers, microgravity appeared to create little difference from the microstructures produced in a gravity environment.

Investigators have also used tertiary elements to improve the microstructure in copper-lead alloys [17]. Some of these elements include nickel, zinc, tin, silver and iron in percentages up to 2-4%. The solubility of many of these elements in copper was excellent and this subsequently allowed the lead to wet the surface of these alloys. This resulted in a range of microstructures that have been well characterized and which appear to be better than the conventional non equilibrium copper-lead alloys. Limited research also appears to demonstrate that directional solidification of many of these monotectic alloys were found to result in regular rod-like structures. Similar structures have been observed in other miscibility gap alloys [18].

Over the years, metallurgists have tried to develop process related techniques to overcome the immiscibility of lead with various metals. The most frequently used process for producing high lead mixtures is by "quick" freezing the molten metal. This method forces the lead to solidify in the copper matrix by entrapping islands of lead which vary in size and shape and is dependent on the cooling process. Unfortunately, "quick" cooling or rapid solidification techniques do not necessarily create a solid solution and thus the immiscibility problem between copper and lead continues to exist. Thus, the process of rapid cooling is

neither reliable nor controllable and therefore not consistently repeatable. Furthermore, the "quick" cooling process is limited in its applicability to thin wall sections, and consequently, cannot be useful for any large scale sections such as those produced by sand or centrifugal casting techniques.

Continuous casting has been used extensively by the steel industry and some limited facilities around the world have adapted this method of production for non-ferrous alloys. In continuous casting of solid rods, one type of general casting system utilizes a stationary die which moves intermittently in a longitudinal manner resulting thereby in the formation of the ingot. During the withdrawal stroke, the casting moves fast enough so that liquid metal enters the cooled length of the die causing intimate die-metal contact. This stroke is followed by a dwell period during which the casting is stopped or slowed so that it will exit from the solidification zone at the proper temperature.

However, in many cases, non equilibrium microstructures are generated because of the gross directional solidification that results when the material transitions from the liquid to the solid state. Such gross directional solidification results when the crystals or grains grow in a direction opposite to the direction of heat flow. Mechanical working of such non-uniform microstructures results in cracks and imperfections that renders the product unfit for any engineering application. In cases where the liquid metal is extremely hot or the casting speed too slow, the grain structure takes on a coarse configuration that cannot be altered easily during subsequent cold working operations.

Thus continuous cast materials of non ferrous alloys such as copper or aluminum have resulted in gradients across the cross section and the length of the material. While such inhomogeneity is tolerated in some applications, these alloys are <u>unfit for use in tribological applications where uniformity in microstructure is desired</u>.

Recently, a process that utilizes a special die was designed for incorporation in the continuous cast system. The die made of

Recently, a process that utilizes a special die was designed for incorporation in the continuous cast system. The die made of graphite, consists of a plurality of openings or holes located in the die and positioned (unlined) relative to each other in such a manner that a cyclonic or swirling motion is produced in the liquid alloy as it flows into the die. This stirring of the liquid alloy close to the near freezing zone facilitates the fragmentation of the liquid droplets and thus the homogenous distribution of the phases in the solidifying die.

In the case of producing non equilibrium copper-lead alloys and other miscibility gap systems, a new technique that uses proprietary organic and inorganic salts during melting, facilitates the reduction in surface tension between the two metals at elevated temperatures and also induces a vigorous stirring action creating tiny droplets that act as nuclei and form an emulsion instead of the normal mixtures. This facilitates non equilibrium quantities of lead to be dissolved in copper or aluminum melts. The surface tension of the liquids in the copper-lead system at elevated temperatures are illustrated in Figure 2 (14).

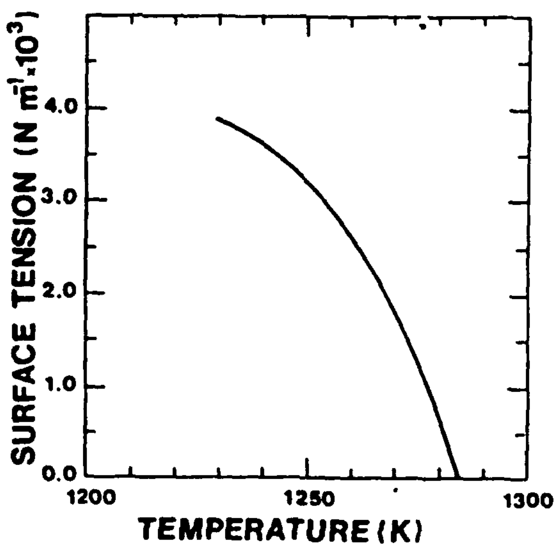


FIGURE 2 Surface tension of the liquids at elevated temperatures in the copper-lead system

Lowering of the surface tension improves miscibility and in combination with the swirl die (facilitates the breaking up of the melt stream prior to solidification) fine grained materials can be produced. Thus, this technique ensures that lead stays homogenous with the copper and can also be continuously cast into bars, rods or tubes up to 9 inches in diameter. Alloys containing up to 60% lead can be produced using this technique under carefully controlled melting conditions.

2. PROCESSING OF COPPER-LEAD ALLOYS

2.1 Continuous Casting Methods

Copper-lead alloys of nominal compositions Cu 90-10 Pb, Cu 75-25 Pb, Cu 50-50 Pb (weight percent) were melted in an induction furnace with a capacity of 2000 lbs. The charge sequence for melting consisted of first adding the copper and waiting for the copper to melt completely and reach a temperature of 1300°C prior to addition of the lead. Due to the large degree of superheat, the lead melts immediately and reduces the temperature of the melt. The temperature was raised again to 1300°C and deoxidant under the trade name of "Phos Copper" marketed by Foseco, Cleveland, Ohio was added to remove the oxides that collect on top of the melt in the form of a slag. Deslagging was achieved by skimming the slag from the surface of the melt. Proprietary additives were then added.

The preparation of the additive consisted of mixing known quantities of sodium carbonate, cupric phosphate, silver sulfide in a beaker and subsequently wrapping them in lead foil in the form of a pouch. Lead foil serves as a excellent carrier for the additives as it sinks to the bottom of the melt during the dissolution process and therefore facilitates intimate mixing with the molten melt. The proprietary additives were always added just prior to casting.

Continuous casting was achieved by using a patented swirl die designed using graphite. The die has angular holes positioned equidistant along the periphery. This causes the molten metal stream to pass through the holes in the die and swirl as it enters

the continuous caster. A combination of the aggressive reactions induced by the additives coupled with the vigorous induced mixing by the swirl die results in a very close control over the microstructure. The draw rate of the motor was adjusted to ensure that only fine grained materials were produced.

All alloys were produced in the form of 3 inch diameter ingots and samples were machined from these ingots for all studies in this research effort. A selected portion of the ingot material was converted to powder using a inert gas atomization process to study the effects of powder metallurgy consolidation methods and properties on component behavior.

2.2 Gas Atomization Methods

The conversion of copper-lead to spherical powder is achieved by a inert gas atomization process. In this process, the ingot produced using the swirl die continuous casting method is first melted in an induction furnace at around 912 - 1083° C and held for five to ten minutes for complete homogenization of composition. A blanket of sodium carbonate is placed over the melt surface to ensure that there is no oxygen pick up from the environment and to also ensure that the lead and the copper stay mixed in solution at the elevated temperature. A nozzle at the bottom of the holding pot allows the flow of the molten metal stream into the atomization chamber for conversion to powder. The nozzle can be plugged or unplugged with a stainless steel stopper rod that has a pointed V shaped configuration. A typical schematic of the gas atomization process is shown in Figure 3.

A low porosity (less than 5 %) zirconia nozzle available from Zircoa (Union Carbide subsidiary) was used in all the powder conversion experiments. The crucible containing the hot metal (copper-lead) is placed over the atomization chamber and the stopper rod is removed. The metal flows in a cylindrical stream and is met by a perpendicularly injected gas flow of nitrogen through a annular ring in the atomization chamber. The pressure of the gas determines the ability to break the molten metal stream into

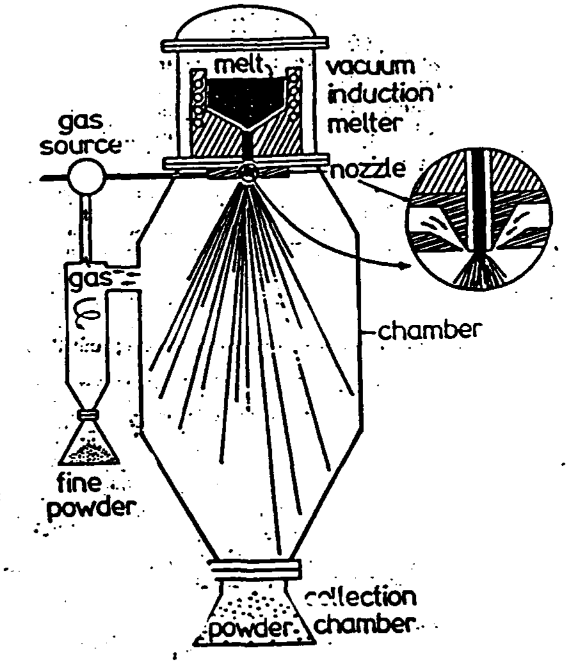


FIGURE 3 Typical set up for Inert Gas Atomization

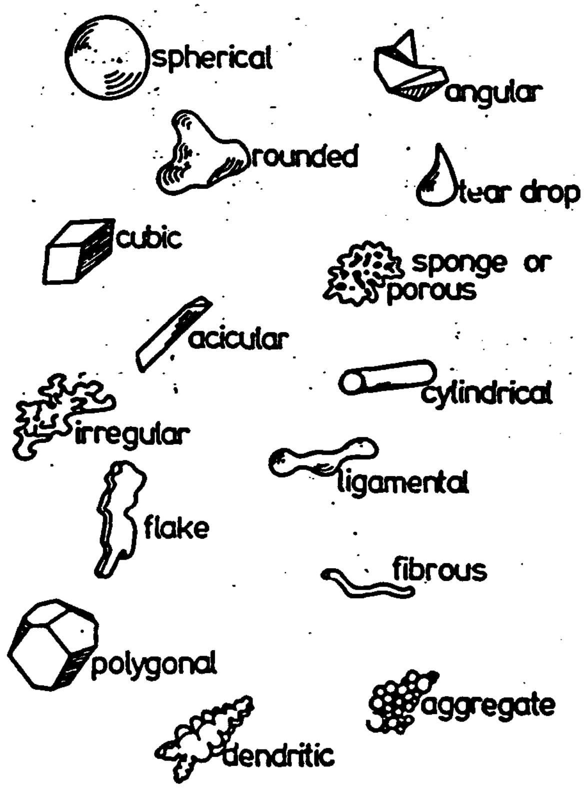


FIGURE 4 Typical powder morphology produced in alloys

droplets. The process of free fall solidifies the droplets and collects at the bottom of the atomization chamber as a solidified powder. A range of powder sizes is produced in any inert gas atomization process and careful control over pressure can maximize the creation of a particular powder size and shape. Lower pressures and use of gases such as helium, argon, hydrogen or oxygen can result in the formation of powders of different shapes other than spherical. Typical powder shapes are illustrated in Figure 4.

If coarse spherical powders are desired (+325 mesh to -100 mesh) low pressures (200-250 psi) are used, if very fine spherical powders are desired (-325 mesh), higher pressures are desired (250-400 psi). Since most powder metallurgy products use coarse powder to achieve uniform sintering characteristics, we chose the 200-250 psi range for the pressure of the inert nitrogen. This ensured that we had uniformly round powders independent of composition.

In any inert gas atomization system, a certain proportion of the powders also end up in the very fine range and are collected in a cyclone separator that is located in the gas atomization chamber. One of the major problems noticed during production was the corrosive nature of the hot metal. As the lead content increased the nozzles were badly eroded. This can be attributed to the infiltration of the pores in the nozzle by the hot metal and the chemical attack that occurs along the grain boundaries between the lead rich metal and zirconia.

After atomization, the powder that is collected in the cyclone separator and the container at the bottom of the chamber were subjected to sieve analysis. This ensures a clean mixing of the different powder sizes for further use in powder metallurgy applications. The powder was classified into three sizes by using mechanical sieve shakers with three different sieves. The sizes were -325 mesh, +325 to -100 mesh and +100 mesh. The different sizes were then packed in plastic lined drums and carefully sealed with silica gel to ensure that no moisture contaminated the raw material powders. Optical and scanning electron microscopy was performed on the typical spherical powders (different sizes) and

are displayed in Figures 5-6. Homogenous spherical powders were observed in all the three different compositions and the two different sizes (-325 mesh and +325 to -100 mesh).

3. CONSOLIDATION METHODS

3.1 Shock Compaction

Shock compaction is an extremely rapid near net shape technique for consolidation of powders. It has been used in the past to consolidate compositions in shapes or forms that are very difficult by any of the conventional heat assisted consolidation techniques. When a shock wave is applied and is traveling at a high velocity, the heat generated between the packed powder particles creates interparticle friction and hence localized fusion. If proper conditions are applied the materials can form consolidated products that are near theoretical density.

In the case of atomized copper-lead powders that have fine distributions of lead dispersed in the matrix, consolidation using sustained exposure to thermal sources will result in diffusion of the lead to the exterior surface and possible agglomeration of the lead. This is not desired if both self lubricating and mechanical properties are desired. Hence techniques that can minimize any diffusion of lead and maintain the fine distribution in the copper matrix are preferred.

In "Shock Compaction" of copper-lead powders, the lead distribution can be retained in the fine form such that extremely good self lubrication will be feasible without a compromise in the mechanical properties thereby ensuring a long life for the bearings, cages or bushings. A typical set up for a "Shock Compaction" experiment is shown in Figure 7.

In the shock wave compaction set up, powders of the three different compositions were packed into a hollow steel cylinder of 42 inch length and 3.5 inch diameter. This cylinder is then enclosed in a larger diameter (4.5 inch) pipe of the same length. Each of the three compositions had two sizes of powders, the +325 mesh to -100 mesh (coarse powders) and -325 mesh, (fine powders).

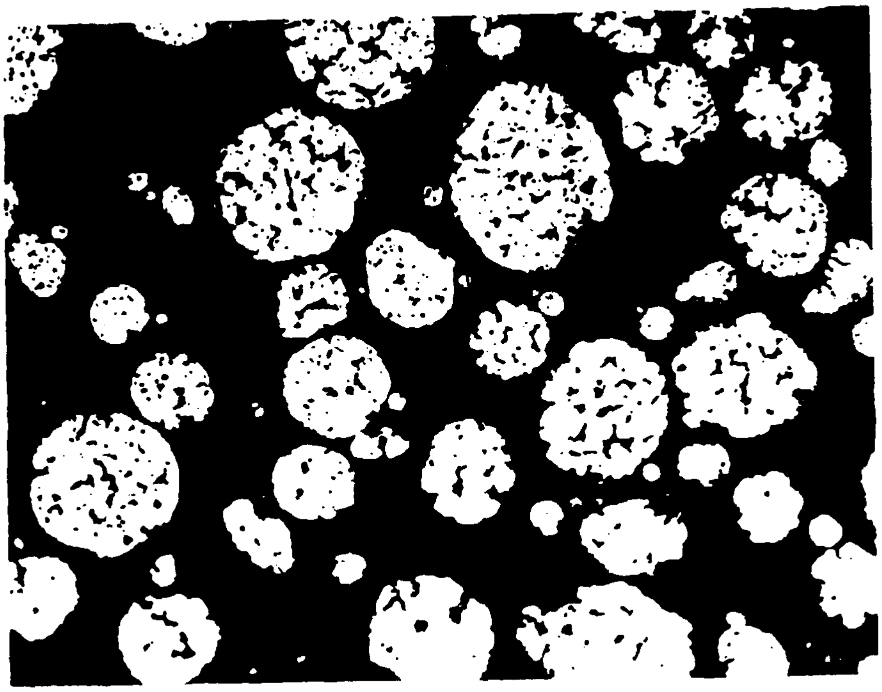


FIGURE 5 Optical microscopy of spherical copper-lead powders (Magnification 750X)

FIGURE 6 SEM of typical spherical powders (Magnification 200X)

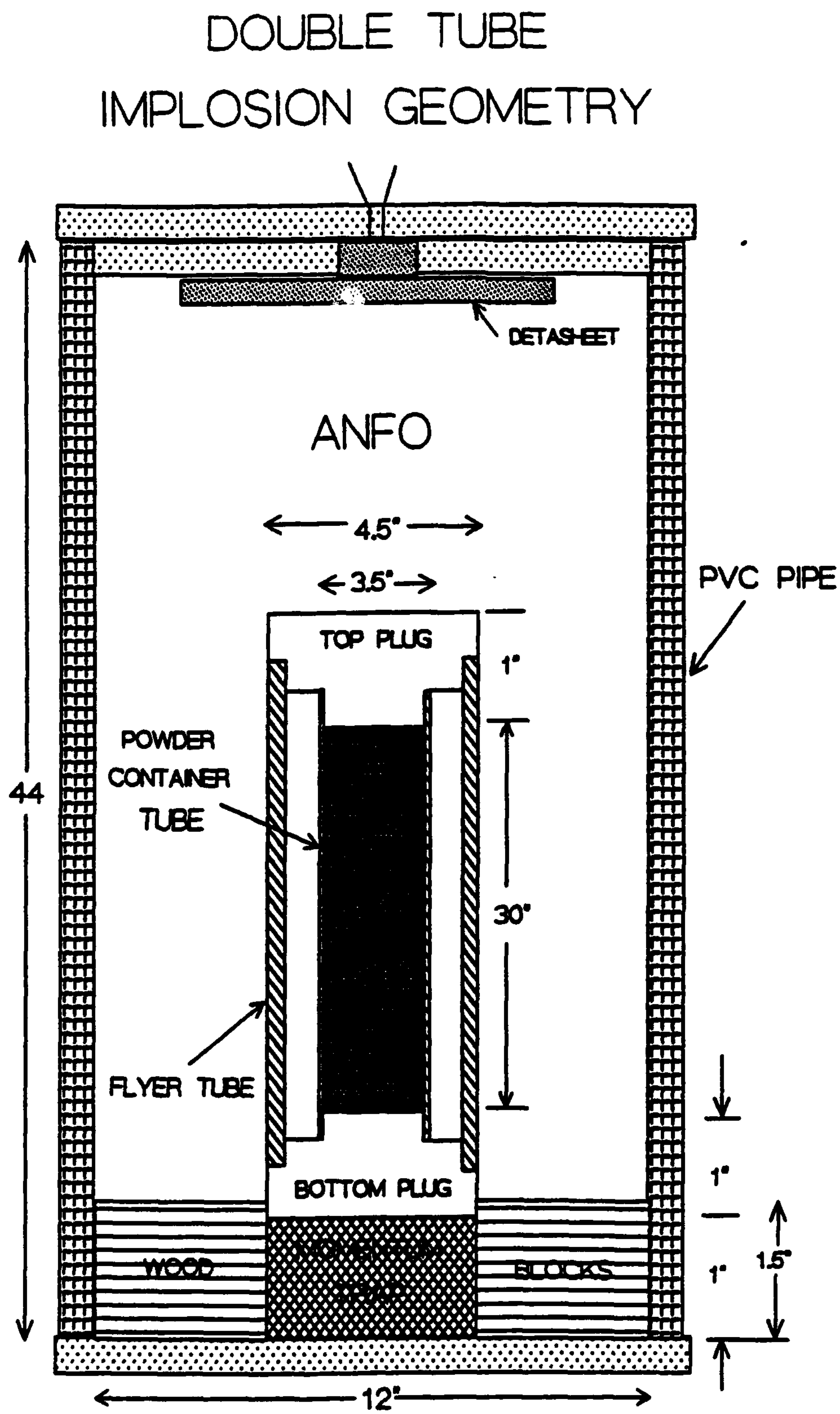


FIGURE 7 Typical set up for a "Shock compaction" experiment

The powders were packed by tapping and gentle shaking of the steel cylinder and the density of packing was calculated to be 59-62%. This is the normal packing density for the hollow cylinder configuration.

The cylinders were placed in a 12" inch diameter plastic tube and Ammonium Nitrate mixed with diesel oil and termed commercially as ANFO was packed in the space between the steel and the plastic cylinders. A flat wooden plate was placed on top of the pipe and a detonator fuse was attached to the system. The other end of the fuse was attached to the power discharge system.

The power discharge system consists of a charge-discharge capacitor. A short circuit was created by discharging the power into the fuse creating a spark that ignites the ANFO. The shock wave that is created due to this process moves from top to bottom and from the outside to inside of the cylinder at about 1.5 km/sec. This creates tremendous interparticle friction (plastic deformation) between the powder particles and thereby generates incipient fusion of the particles resulting in the formation of an ingot.

Six ingots were produced (three compositions of two particle sizes each). During machining of the outer steel sleeve, the -325 mesh ingot of 50/50 copper-lead composition fractured at several locations probably due to the high internal stresses developed during shock compaction. Only small selected regions were free of cracks and for all practical purposes it was difficult to salvage sections that would be large enough to produce components. Hence 50/50 (-325 mesh) copper-lead "Shock Compacted" ingots were not available for friction and wear or component testing. The typical microstructure of a "Shock Compacted" ingot is shown in Figure 8. The interesting feature observed was the extra fine structure within the grains of the ingot. The dark areas represent lead and the white areas represent copper. No other known metallurgical process can create such fine grain sizes in such large ingots other than shock-wave compaction.

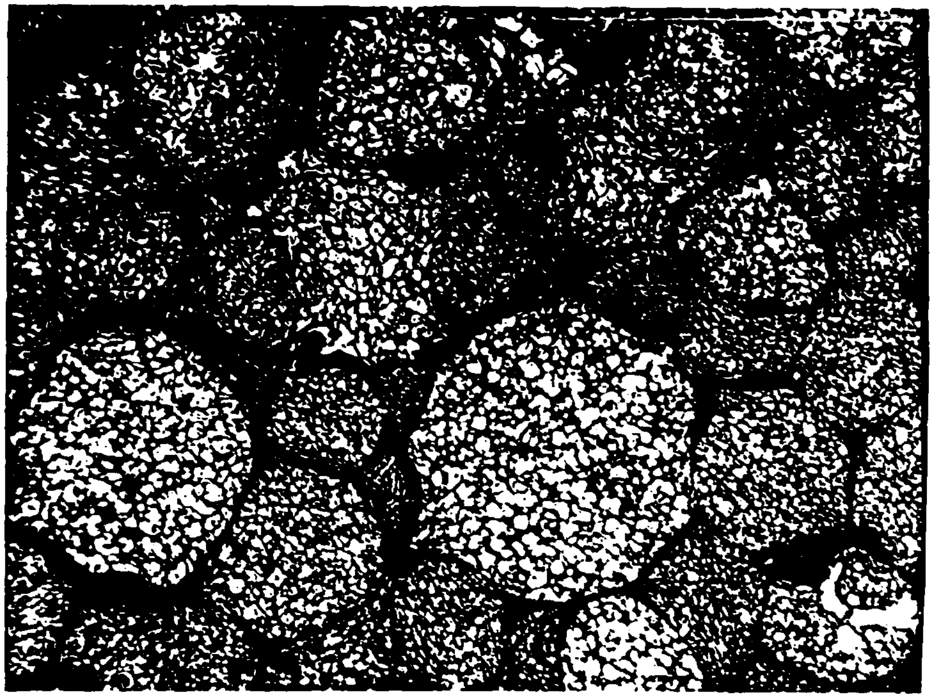


FIGURE 8 Typical microstructure of a "Shock Compacted" copper-lead alloy (Magnification 400X)

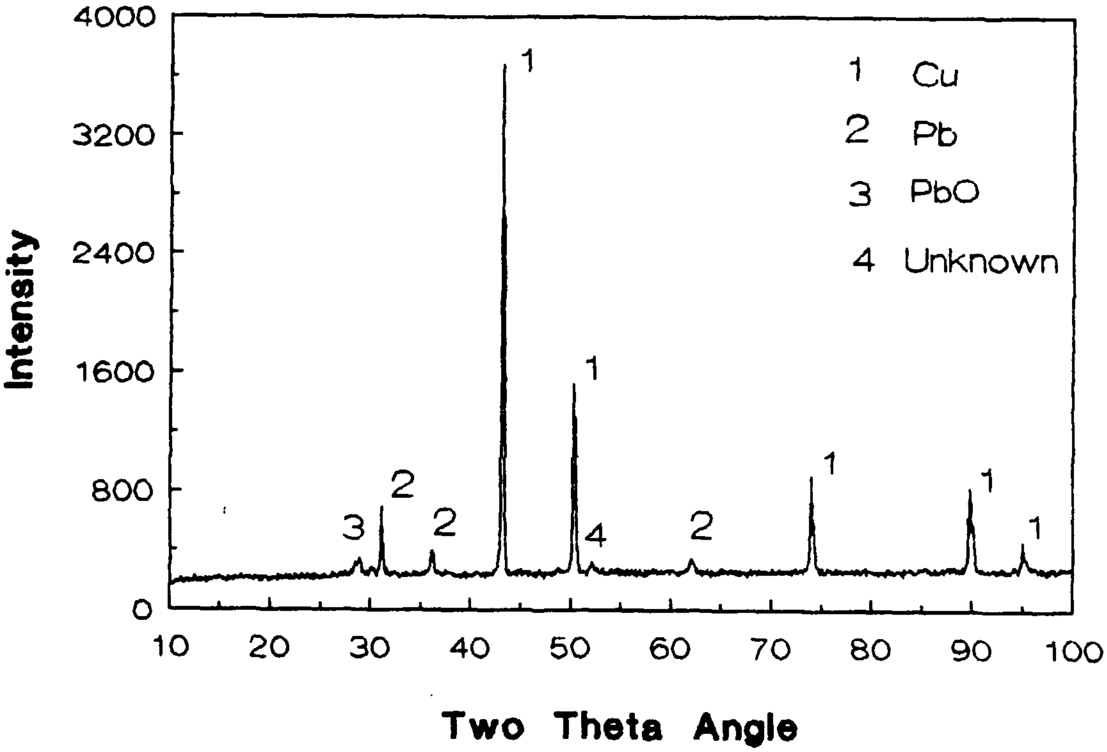


FIGURE 9 Typical x-ray pattern for "Shock Compacted" copper-lead ingot

X-ray diffraction studies on the "Shock Compacted" samples showed presence of both copper and lead and a small amount of lead oxide. A typical x-ray pattern is shown in Figure 9.

Friction and wear studies were performed using a ball on flat machine and component life testing was performed on test rigs specially designed for space environment simulation by the National Council for Tribology (NCT) U.K. Tests were run on the different ingots produced using the "Shock Compaction" process.

3.2 Hot Isostatic Pressing (HIP'ping)

Hot Isostatic Pressing ("HIP'ping") was used to fabricate bars of the various gas atomized powder materials. "Hip'ping" was performed at 750°C for one hour under an argon gas pressure of 103 MPa. All "HIP'ping" was performed by HIP Ltd in Derbyshire, U.K.. Mild steel capsules (65 mm diameter x 95 mm long) were used to produce the "HIP'ped" samples. The nominal size of the bar produced after "HIP'ping" was 42 mm diameter x 75 mm long. A mild steel foil washer and smaller diameter foil plate were placed on top of the powder to be compacted and a mild steel lid was welded onto the steel capsule and an evacuation tube attached. The presence of the foil sections was to prevent the loss of the fine powder during evacuation. The capsules were evacuated using a double stage rotary pump to a pressure less than 1 x 10^{-2} mbar. Sealing of the capsules was achieved by hot crimping the evacuation tubes while under vacuum. Each capsule was individually "HIP'ped" to achieved densification. The HIP'ping studies revealed the following observations:

a) The 90-10 and the 75-25 developed good interparticle bonding and very little lead segregation except a small layer on the outermost surface. This suggests that the gas atomized powders had indeed locked the lead inside the copper matrix thereby preventing leaching of the lead and the loss of its lubricating ability. (See Figure 10.)

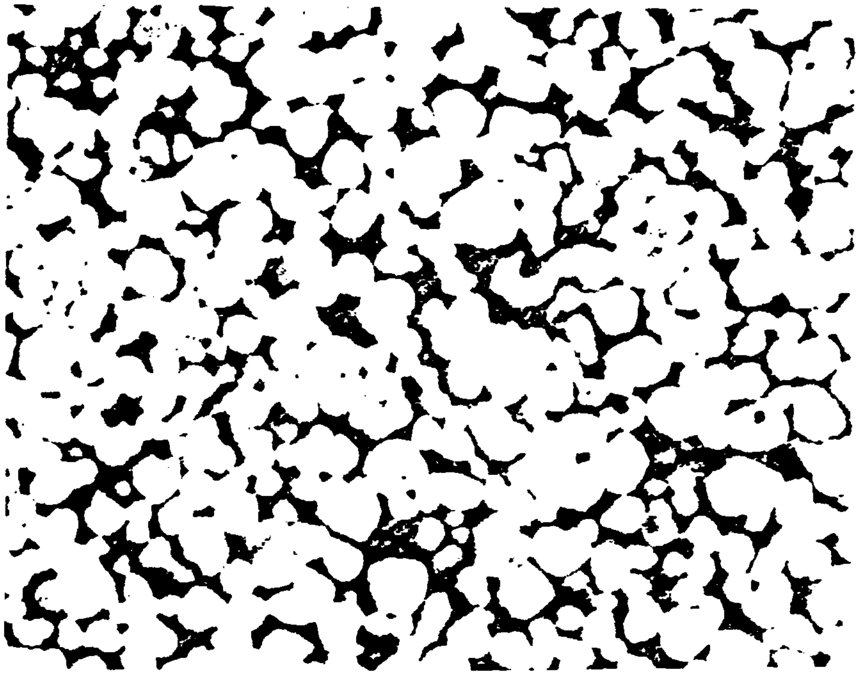


FIGURE 10 Interparticle bonding of 90/10 & 75/25 copper-lead composition samples (Magnification 200X)

FIGURE 11 50/50 billet coated with lead segregation at grain bond (Magnification 50X)

b) The 50-50 billet was coated with a film of lead and some lead segregation at the grain boundaries was observed. (See Figure 11.) There was also a gradient in the density across the diameter of the bar. This suggests that the "HIP'ping" parameters used were approaching the melting temperatures of lead and hence some amount of fluidity of the lead resulted in the coating of the particles.

4.0 FRICTION AND WEAR STUDIES

Flat disks of 2" diameter and 0.25" thickness were machined from the ingots that were "As Cast" (AC), "Shock Compacted (SC), or "HIP'ped" (HIP) and used in all the friction and wear studies. The tests were performed using a ball on flat disk machine. The ball was 5/16" diameter 52100 hardened to HR_C 50. Although the temperature and humidity were not continuously controlled, the tests were run in conditions between 65°F - 73°F and relative humidity of 27 - 50%. Each set of copper-lead disk and steel ball were thoroughly cleaned in an ultrasonic cleaner using methanol for approximately 2 minutes. The weights of the ball and copper-lead disk were recorded before and after each test. After the friction test was completed the disk samples were again cleaned in methanol and the difference in weight was used for calculation of volume loss. Since there was no substantial weight gain for the ball, only the weight loss for the disk was taken into account for calculating the volume loss for each sample.

The friction tests were performed in a computer controlled system, by allowing the stationary ball to rub against the plane surface of the rotating sample. Three different sliding speeds (0.05 m/s, 0.10 m/s and 0.15 m/s) and normal pressures ranging from .07 MPa to .42 MPa (which correspond to 250 grams to 1500 grams axial load) were applied to the surface of the sample. All samples were tested for a total sliding distance of 1000 meters.

The force resulting from the friction between the ball and disk was measured by a transducer and recorded by a computer. A Q Basic computer program designed for this machine was used to

acquire the data at regular intervals so that the calculated values could be displayed on the computer screen in terms of the coefficient of friction versus time (sec). The coefficient of friction is defined as:

Coefficient of friction (μ) = Force / Applied load

The data derived from the test related to the coefficient of friction was averaged and plotted as a data point by the computer every 5 - 20 seconds depending on the sliding speed.

Volume loss for each disk was calculated by measuring the mass loss.

Volume loss, mm^3 = Mass Loss, (g) X 1000/ Density, g/cm^3

Since each copper-lead composition was based on weight percent, the density was an average of the densities of copper (8.93 g/cm^3) and lead (11.38 g/cm^3) in the appropriate ratios. (See Table 2)

TABLE 2 Average Density of Copper-Lead Alloys

COMPOSITION	DENSITY g/cm^3
50/50	9.13
75/25	9.44
90/10	10.01

By calculating the volume loss, the specific wear rate was calculated for each material and sample tested.

Specific Wear Rate = Volume loss, mm^3 / Normal force (N) X distance (M)

The Normal force is defined as:

Normal force = Gravity (M/s^2) X Load (kg)

4.1 Friction Studies

The coefficient of friction for the varying processes and specific compositions tested in this program are shown as a function of load and composition (Figures 12A - 12C) and as a function of sliding speed (Figures 13A - 13C). A complete listing of all the data collected in this program is shown in Table 3. The principal observations are:

- An increase in applied load resulted in a decrease in friction independent of sliding speed, composition, or manufacturing /consolidation processes.
- Increase in the lead content generally resulted in an increase in friction for all the processing conditions evaluated in this study. This could be attributed to the rapid formation of a film and its subsequent oxidation to PbO that is brittle and hence promotes formation of debris.
- Increase in sliding speed resulted in increase in friction for all the "HIP'ped" compositions. This occured probably due to the easy break up of the particles and their subsequent oxidation. In contrast the "As Cast" materials demonstrated minimal changes in the friction values except in the case of 50/50 where an increase was observed at lower sliding speeds. This could be attributed to the distribution of lead within the matrix and the ability of the "As Cast" materials to rapidly form a transfer film.
- Changes in particle size did not affect the friction values for all loads, compositions, or sliding speeds.
- For all the different conditions tested in this program the "HIP'ped" compositions had the most consistent values. (See Table 3.)

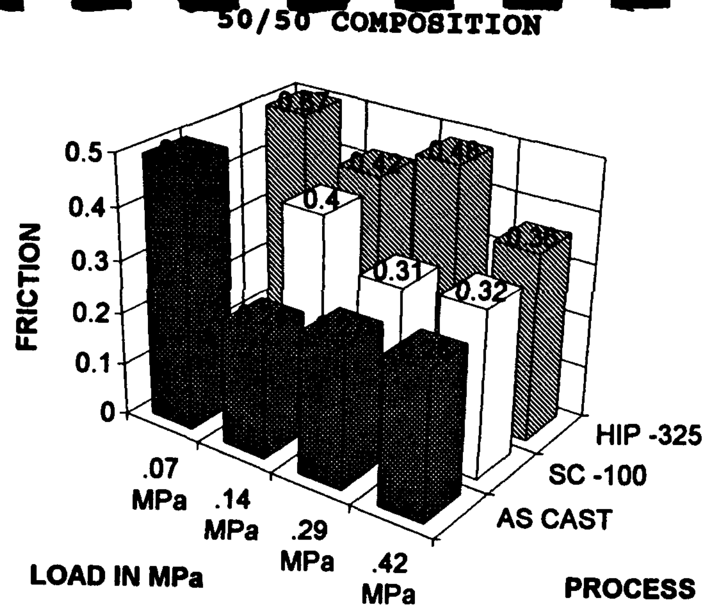


FIG. A

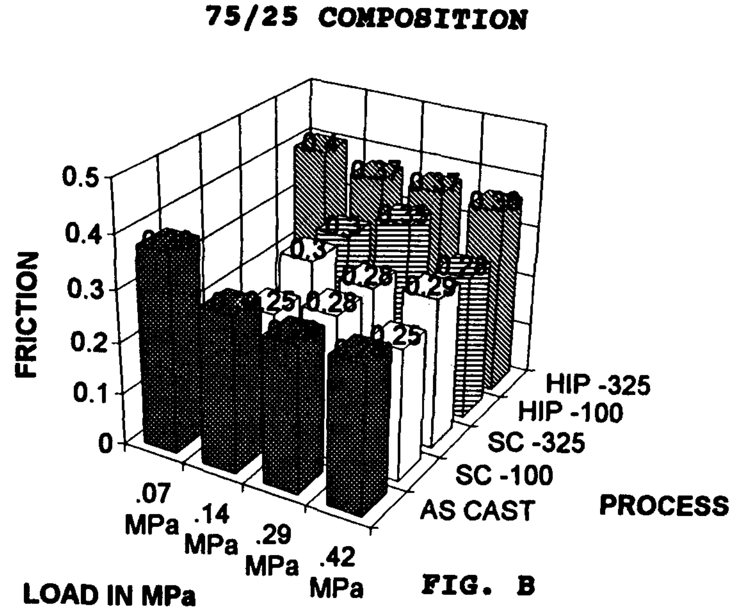


FIG. B

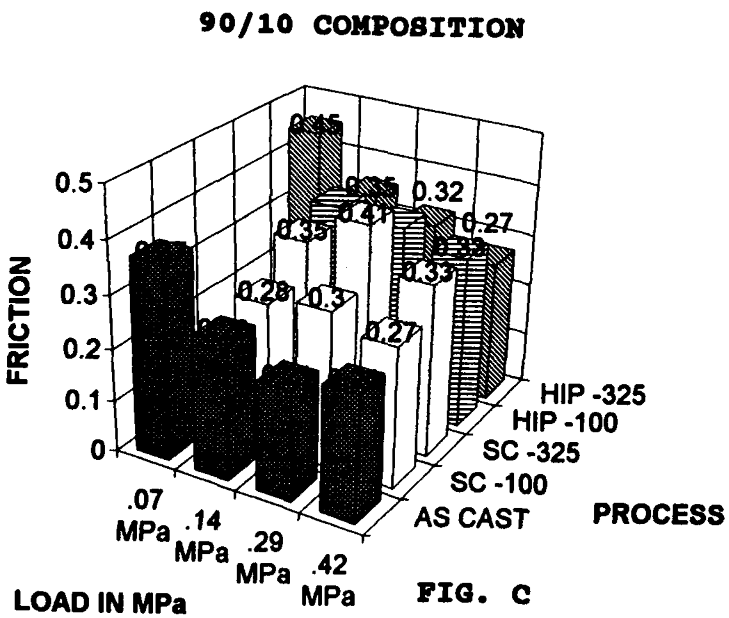


FIG. C

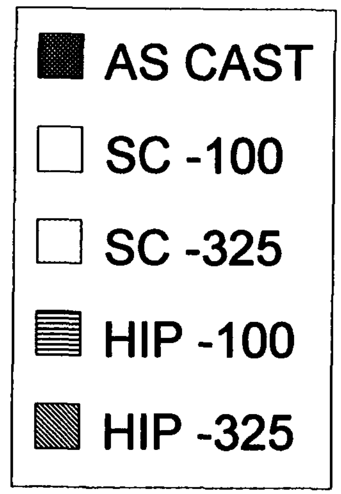


FIGURE 12 Friction as a function of load and process for various compositions of copper-lead alloys at a sliding speed of .15 m/s

50/50 COMPOSITION

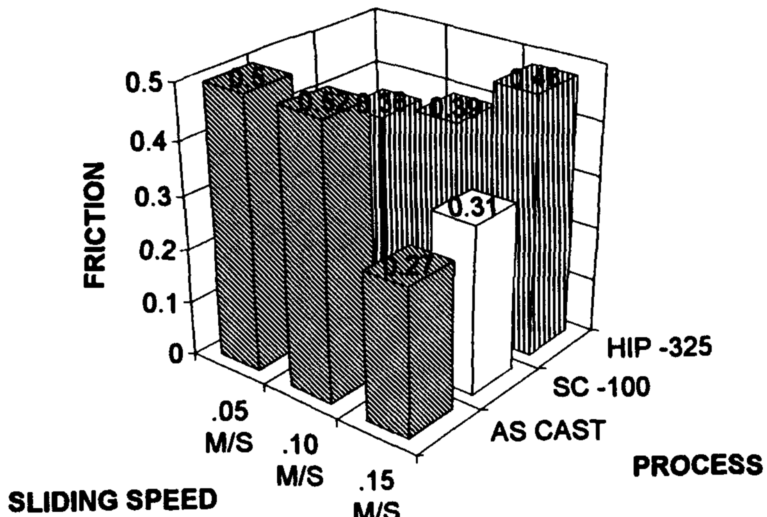


FIG. A

75/25 COMPOSITION

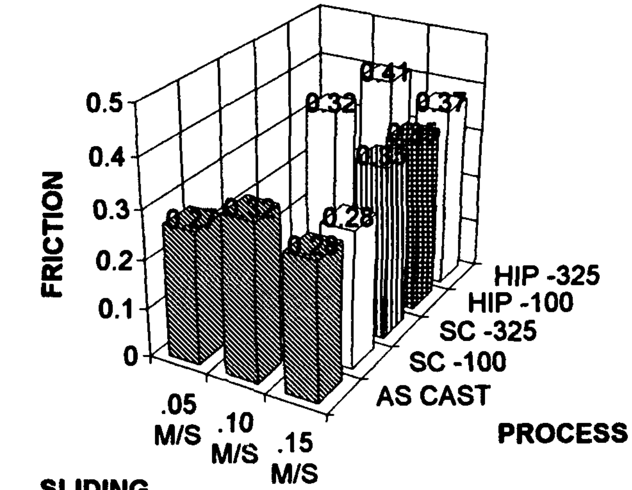


FIG. B

90/10 COMPOSITION

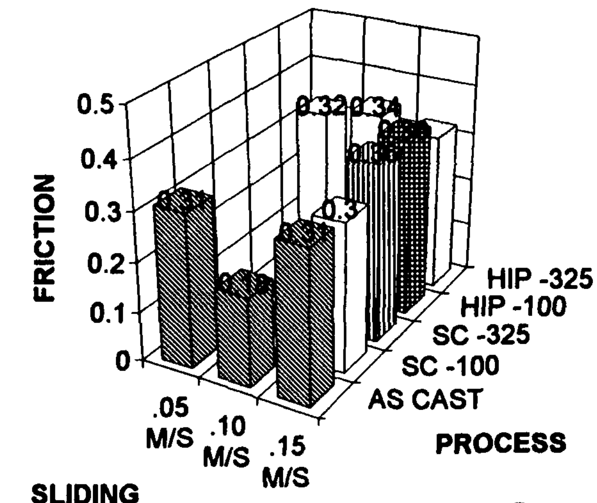


FIG. C

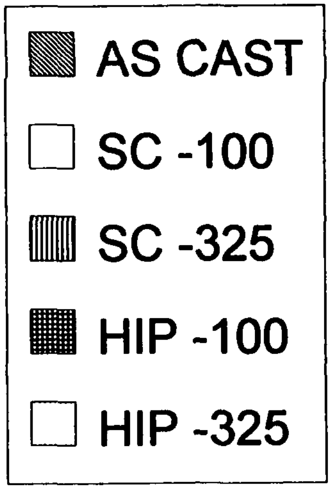


FIGURE 13 Friction as a function of sliding speed and process at a load of .29 MPa for various compositions

TABLE 3 COEFFICIENT OF (μ)
(AVERAGE OF TWO TESTS)
SLIDING DISTANCE = 1000 METERS

	AS CAST			HIP'PED -325 MESH			HIP'PED -100 MESH	SHOCK COMP -325	SHOCK COMP -100
	SLIDING SPEED IN M/S								
LOAD (G) & COMPOSITION	0.05	0.10	0.15	0.05	0.10	0.15	0.15	0.15	0.15
250 G (50/50)	0.35	0.76	0.59	0.50	0.51	0.67	--	--	--
500 G (50/50)	0.40	0.41	0.24	0.33	0.43	0.42	--	--	0.40
1000 G (50/50)	0.50	0.52	0.27	0.36	0.39	0.48	--	--	0.31
1500 G (50/50)	--	--	0.28	--	--	0.36	--	--	0.32
250 G (75/25)	0.37	0.26	0.38	0.38	0.42	0.40	--	--	--
500 G (75/25)	0.26	0.35	0.30	0.32	0.40	0.37	0.30	0.30	0.25
1000 G (75/25)	0.27	0.32	0.28	0.32	0.41	0.37	0.35	0.35	0.28
1500 G (75/25)	--	--	0.28	--	--	0.36	0.28	0.28	0.25
250 G (90/10)	0.35	0.22	0.37	0.37	0.46	0.45	--	--	--
500 G (90/10)	0.18	0.33	0.26	0.38	0.41	0.35	0.37	0.37	0.28
1000 G (90/10)	0.31	0.28	0.21	0.32	0.34	0.32	0.36	0.36	0.30
1500 G (90/10)	--	--	0.24	--	--	0.27	0.33	0.33	0.27

4.2 Wear Rates

In addition to the friction values, wear rates were calculated for all the tests conducted in this program using the procedure described earlier and are presented in Table 4. The wear data from Table 4 is graphically illustrated as a function of load and process in Figures 14A - 14C and as a function of sliding speed and process in Figures 15A - 15C. The general observations include:

- As lead content decreased below 25% there was a significant increase in the wear rate for all the materials and process conditions tested in this program. This suggests that insufficient material was available to form the transfer film.
- Increase in applied load resulted in an increase in the wear rate except in the 50/50 and 75/25 "Shock Compacted" material where there was a tendency for a reduction in the wear rates. This could be attributed to the speed of formation of the transfer film and its subsequent oxidation except in the case of the "shock compacted" samples where the fine distribution of lead may have lead to a more homogeneous formation of the transfer film.
- Increasing the sliding speed, was accompanied by a decrease in wear rate for all compositions and processing conditions.
- The "As Cast" material in all three cases of load, composition, and sliding speed had the lowest wear rate values.
- The "Shock Compacted" material (both meshes -100 + 325 and -325) showed extremely high wear rates especially in the 90/10 composition. Such results may be due to the high stresses present in the material after compaction as no post heat treatment was applied to reduce the stresses.

50/50 COMPOSITION

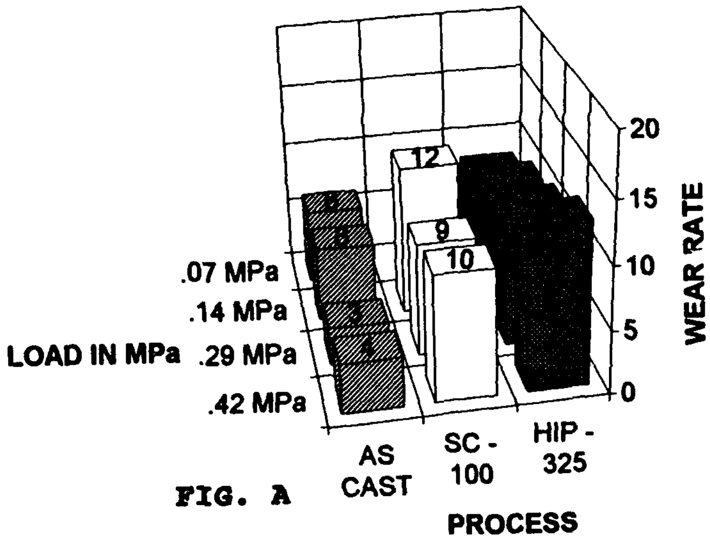


FIG. A

75/25 COMPOSITION

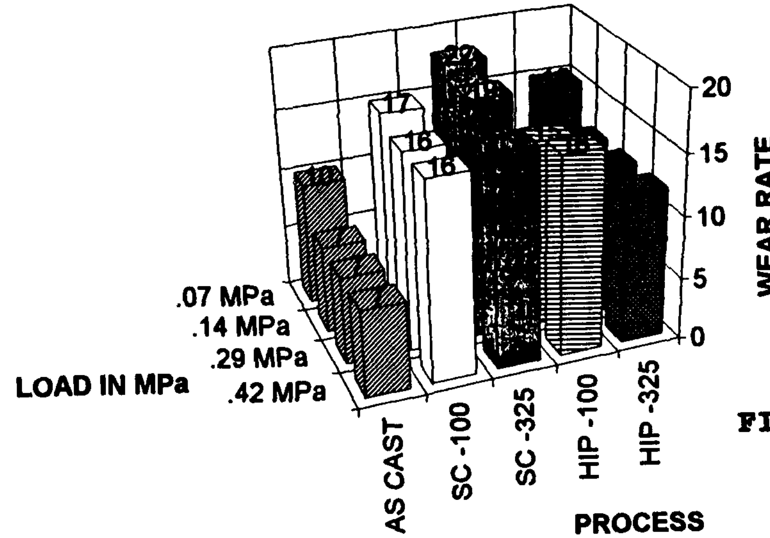


FIG. B

90/10 COMPOSITION

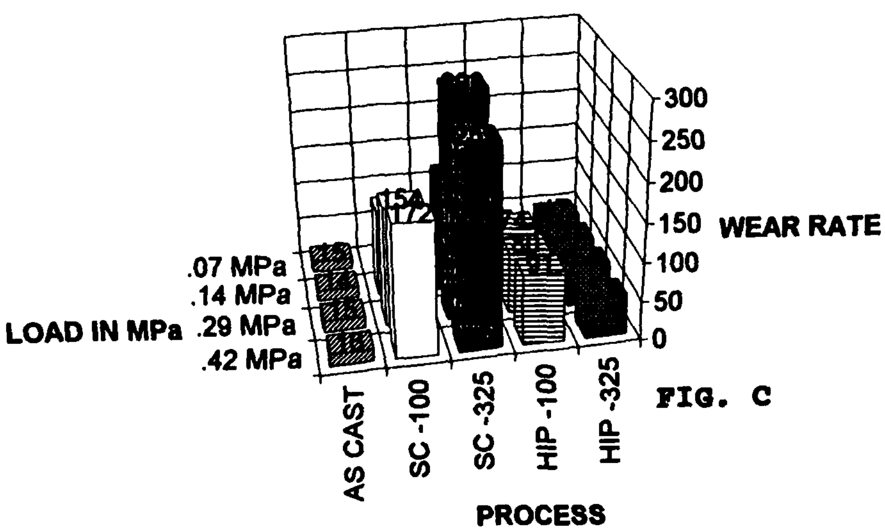


FIG. C

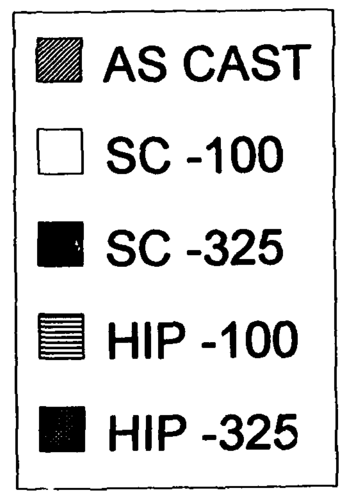


FIGURE 14 Wear rate as a function of load and process for various compositions of copper-lead alloys at a sliding speed of .15 m/s

50/50 COMPOSITION

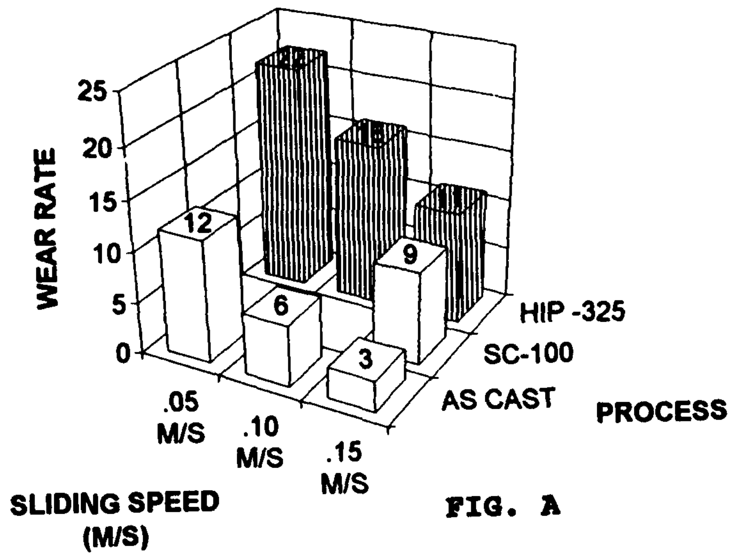


FIG. A

75/25 COMPOSITION

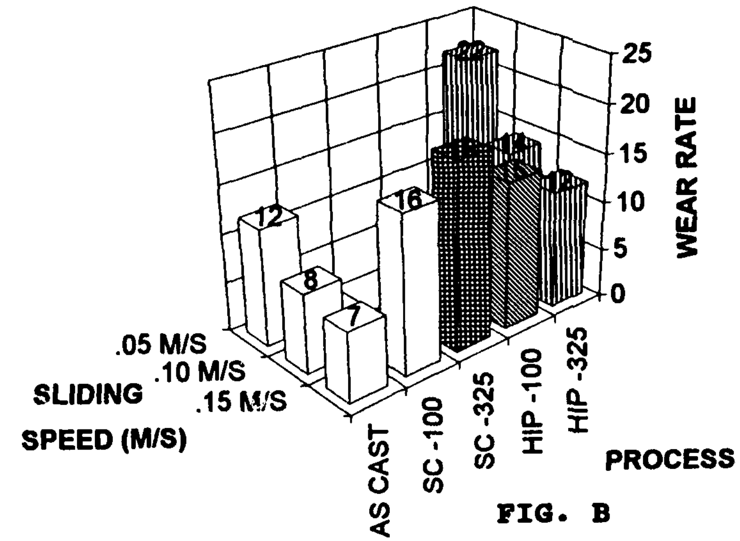


FIG. B

90/10 COMPOSITION

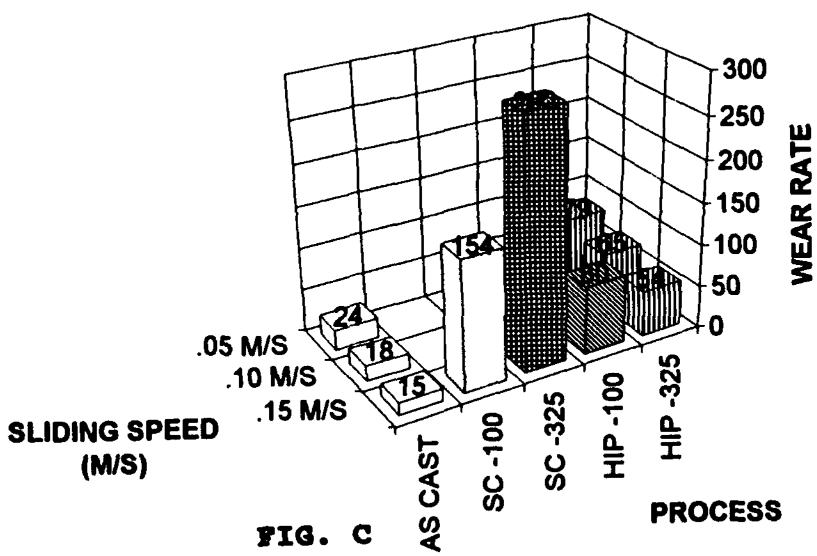


FIG. C

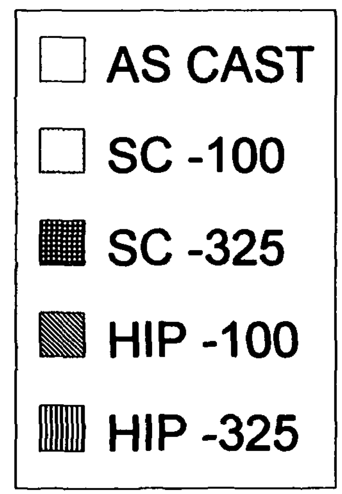


FIGURE 15 Wear rate as a function of sliding speed and process at a load of .29 MPa for various compositions of copper-lead alloys

TABLE 4. WEAR RATES
(AVERAGE OF TWO TESTS)
SLIDING DISTANCE = 1000 METERS
(mm^3 / NM, 1 X E-04)

	AS CAST			HIP'PED -325 MESH			HIP'PED -100 MESH	SHOCK COMP. - 325	SHOCK COMP -100
	SLIDING SPEED IN M/S								
LOAD (G) & CCMPOSITION	0.05	0.10	0.15	0.05	0.10	0.15	0.15	0.15	0.15
250 G (50/50)	9	7	6	22	10	8	--	--	--
500 G (50/50)	8	4	6	31	16	10	--	--	12
1000 G (50/50)	12	6	3	22	16	11	--	--	9
1500 G (50/50)	--	--	4	--	--	13	--	--	10
250 G (75/25)	10	8	10	15	20	15	--	--	--
500 G (75/25)	10	8	7	20	13	12	12	22	17
1000 G (75/25)	12	8	7	22	14	12	15	19	16
1500 G (75/25)	--	--	7	--	--	12	16	17	16
250 G (90/10)	17	16	15	67	53	47	--	--	--
500 G (90/10)	21	16	14	76	83	51	74	151	113
1000 G (90/10)	24	18	15	79	65	54	80	293	154
1500 G (90/10)	--	--	16	--	--	51	91	259	172

5.0 COMPONENT STUDIES (National Council for Tribology U.K.)

Four different types of tribological components that are used in space systems were manufactured using the copper-lead alloys produced in this program for testing in special test rigs available at the National Council for Tribology, UK (NCT). The components were:

- Ball bearing cages,
- Gears,
- Bushings, and,
- Electrical motor brushes.

The manufacture of all these components was undertaken by Premax Engineering Ltd, of Birmingham, United Kingdom who were accredited to follow the quality standards prescribed by British Standards, BS 5750-broadly equivalent to International Standards Organization, ISO 9001.

Figure 16 is a general view of the tribological components tested in this program. The engineering drawings for these components are provided in Figures 17-20. Table 5 provides a detailed summary of the various components manufactured and tested in this program.

One of the inherent limitations of the shock compaction process is reduced ductility (brittle). Hence, no cages or gears which had intricate geometries could be manufactured from the "Shock Compacted" material. The benefits of extremely fine microstructures and thereby the lead distribution derived by the shock compaction process can be optimized only if extensive process parameter studies related to improving the ductility are undertaken. This can facilitate easier manufacturing and the microstructural improvement "Shock Compacted" cages could result in greater benefits than the currently used standard lead bronze.

Figure 21 is a typical example of some of the cracked specimens. The cracked gears also had missing teeth, and in one case the gear blank itself was cracked. The cages manufactured using the "Shock Compacted" material were just too brittle to handle, and some even failed after arrival at NCT during

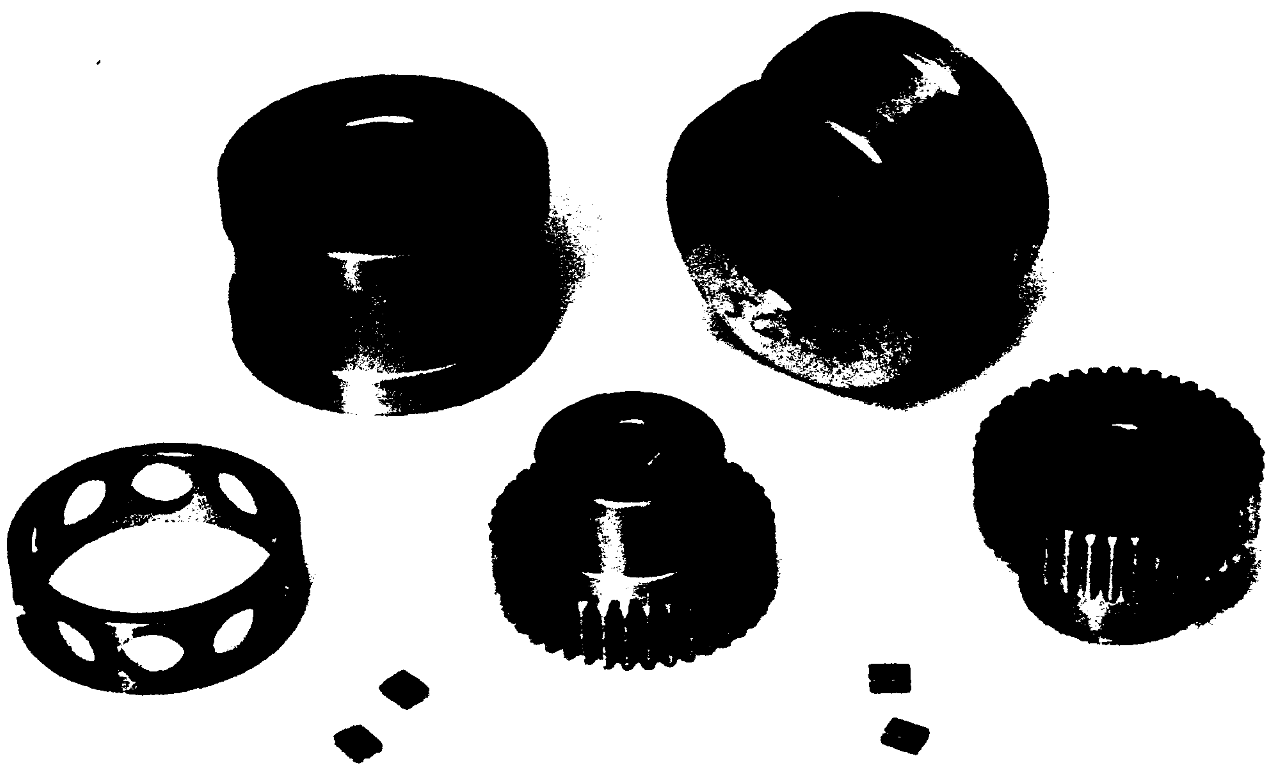
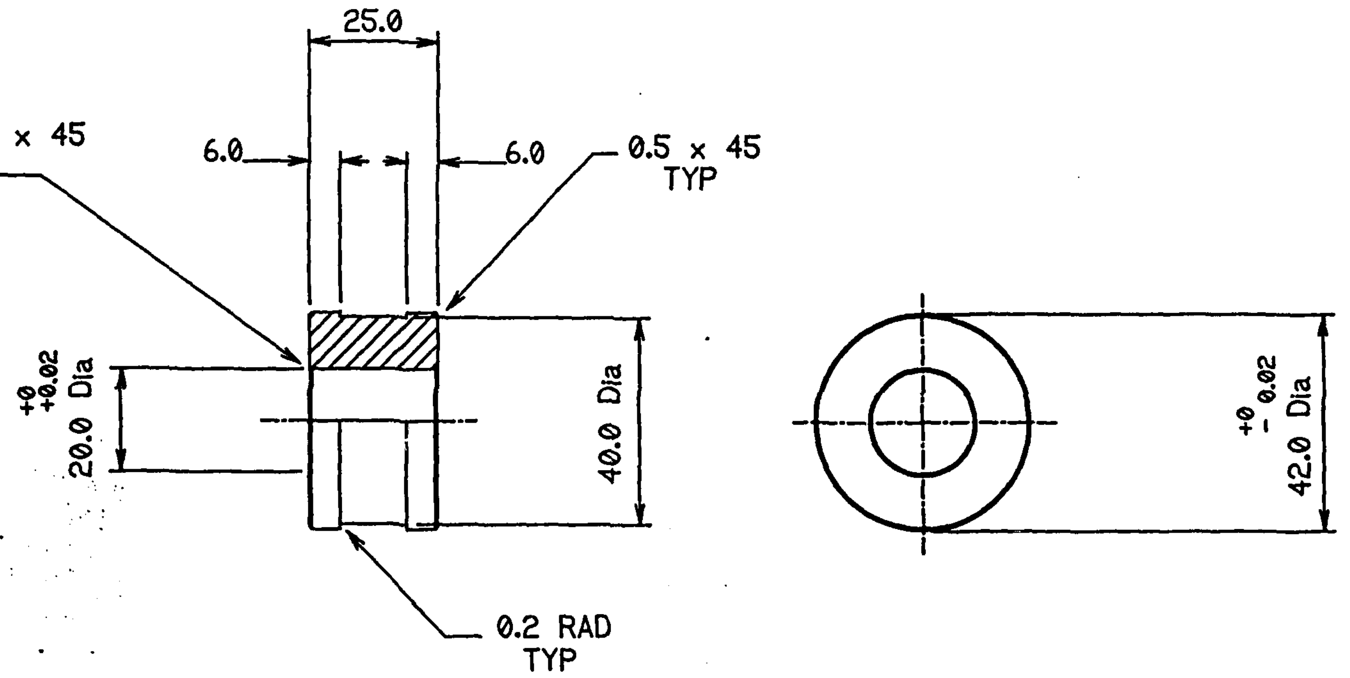


FIGURE 16 General View of the Components for Tribological Testing

Drg No 3AE 1610 10098-01
SHEET 1 of 1



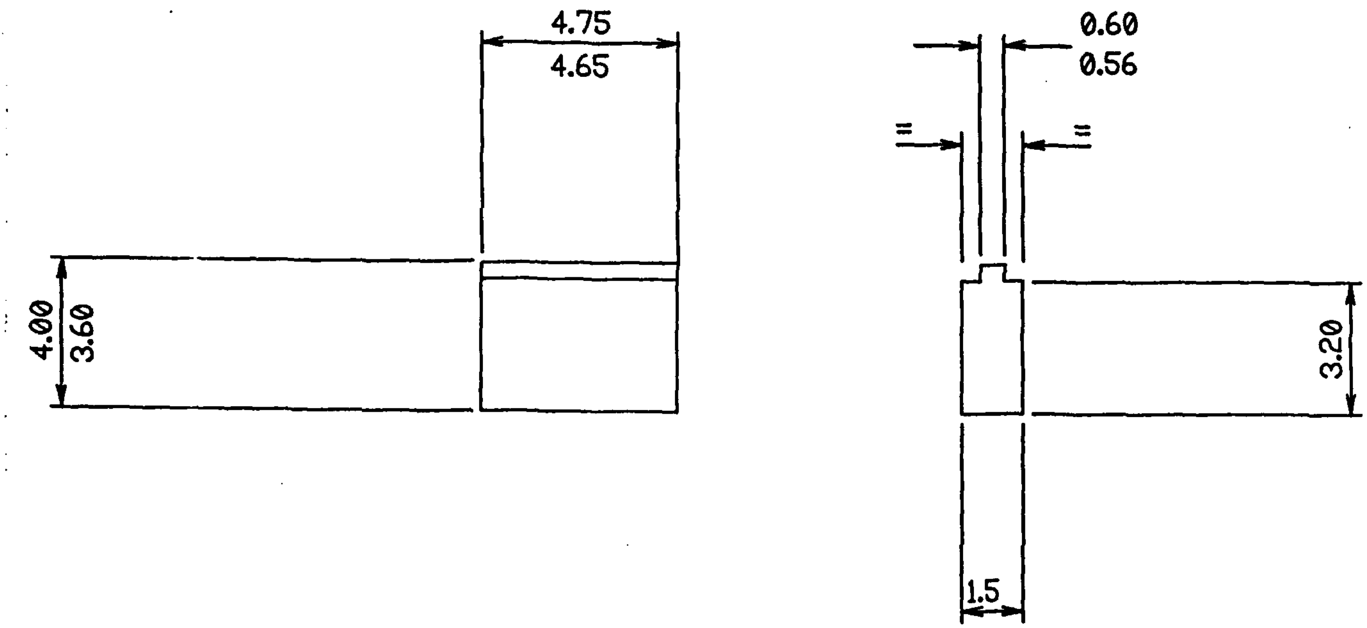
GENERAL NOTES
1. All dimensions in mm unless stated
2. General Tolerances
   +/- 0.2 linear, +/- 0.5 angular
3. NO CUTTING FLUIDS OR ABRASIVES TO BE USED
4. Smooth machine all over, REAM BORE
5. Remove all corners 0.2 rad/chamfer unless stated

MATERIAL:
COPPER LEAD ALLOY
AS SPECIFIED ON ORDER

MOD "B" DRAWING No CHANGED 25-07-91	European Space Tribology Laboratory		
	Drawn: D J Forster	TITLE MMI COPPER LEAD ALLOY TESTS BUSHING	
	Approved:		
	Issued: 01-07-91	Drg No 3AE 1610 10098-01	Issue "B"
	Scale: FULL SIZE	SHEET 1 of 1	

FIGURE 17 Dimensions for a typical bushing

3AE 1610-10098-02
SHEET 1 of 1



GENERAL NOTES
1. All dimensions in mm unless stated
2. General Tolerances
   +/- 0.1 linear, +/- 0.5 angular
3. NO CUTTING FLUIDS OR ABRASIVES TO BE USED
4. Smooth machine all over
5. Remove all corners 0.1 rad/chamfer

MATERIAL:
COPPER LEAD ALLOY
AS SPECIFIED ON ORDER

European Space Tribology Laboratory

MOD "B"	Drawn : D J Forster	TITLE HHE COPPER LEAD ALLOY TESTS
Detail : Drg No changed was 010099-04	Approved :	BRUSHES
Approved :	Issued : 01-07-91	Drg No 3AE 1610 10098-02 — Issue "B"
Issued : 25-07-91	Scale : 8 : 1	SHEET 1 of 1
Drawn : D J F		

FIGURE 18 Dimensions for a typical brush

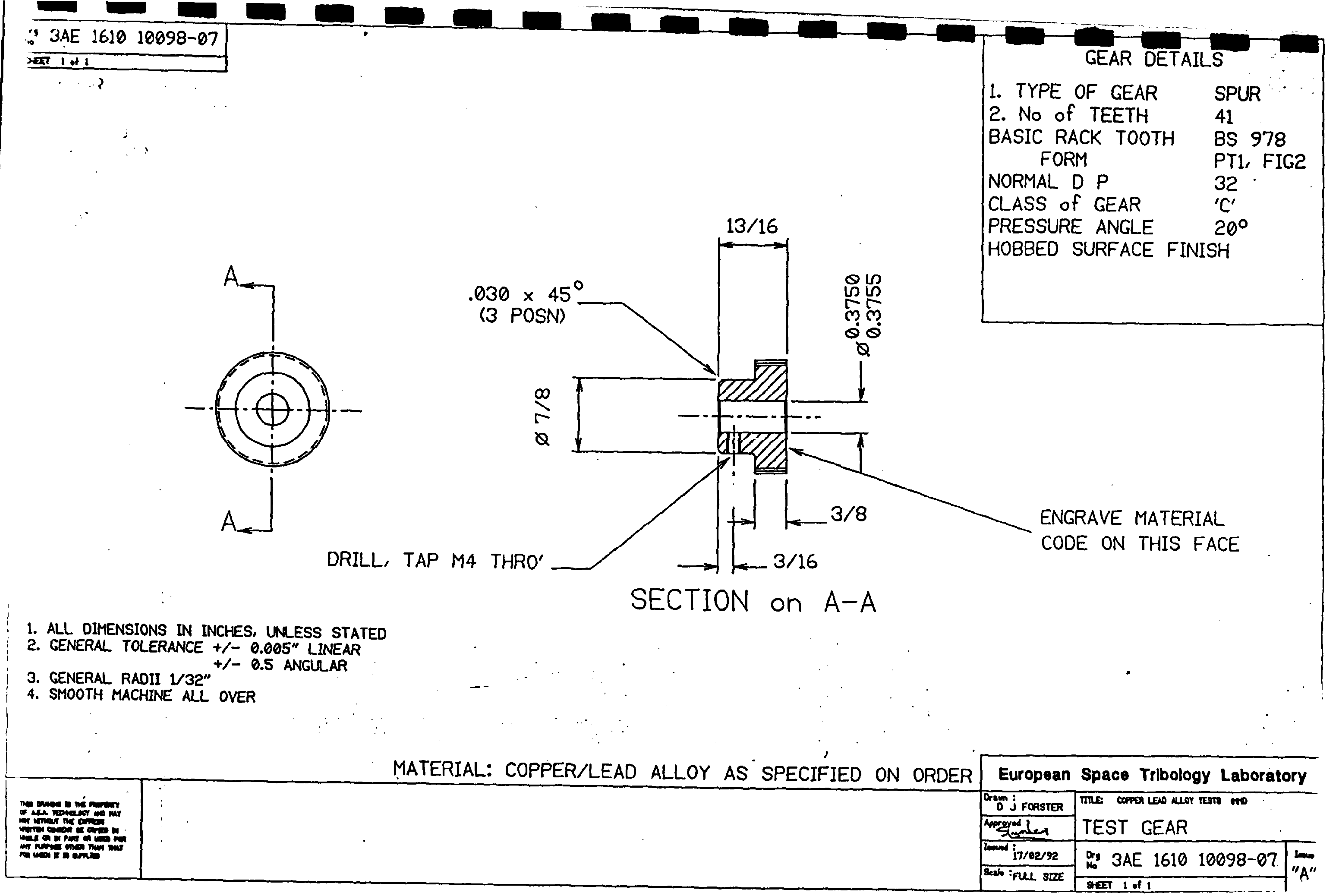


FIGURE 19 Dimensions for a typical Test Gear

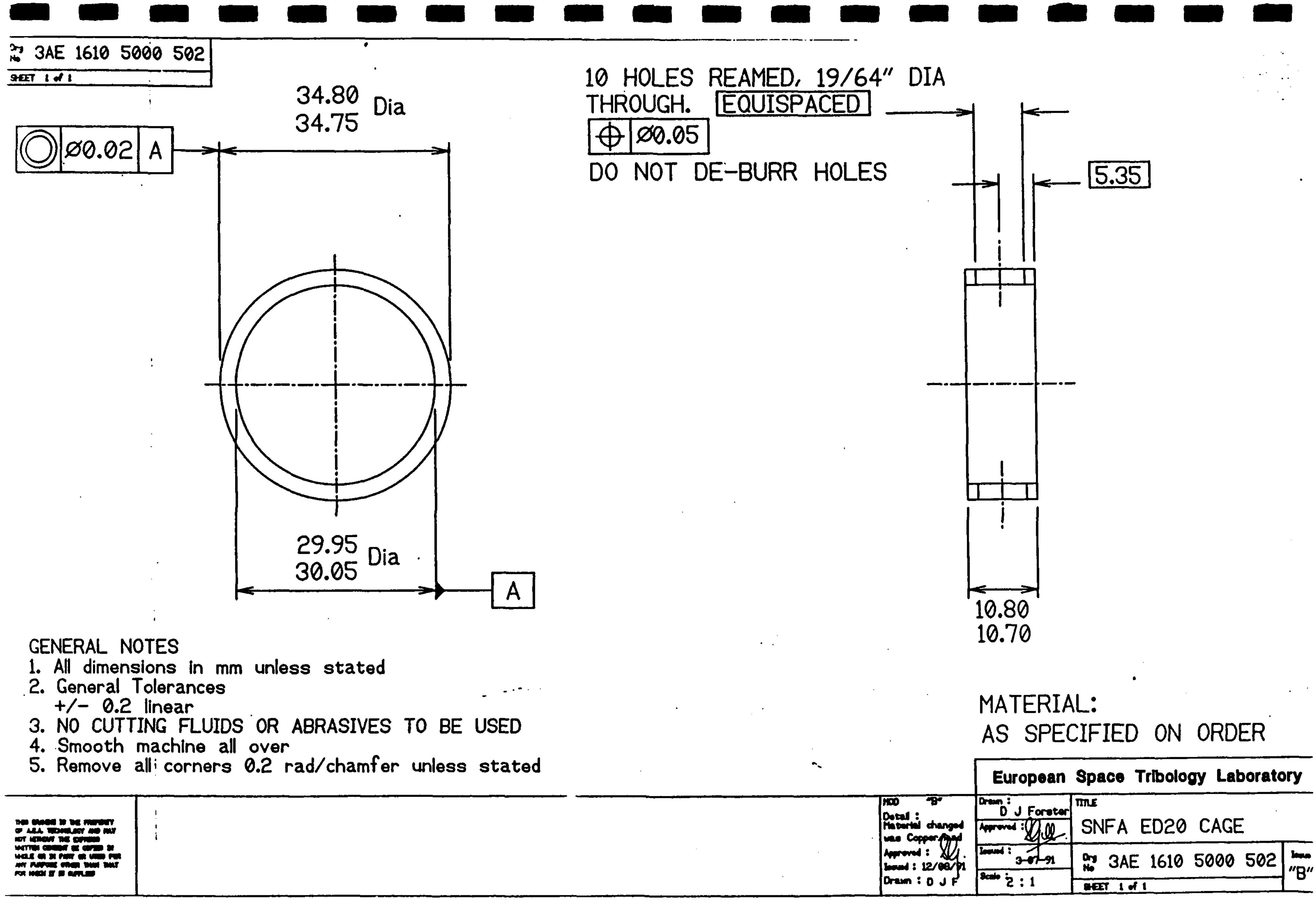


FIGURE 20 Dimensions of a SNFA ED20 Cage

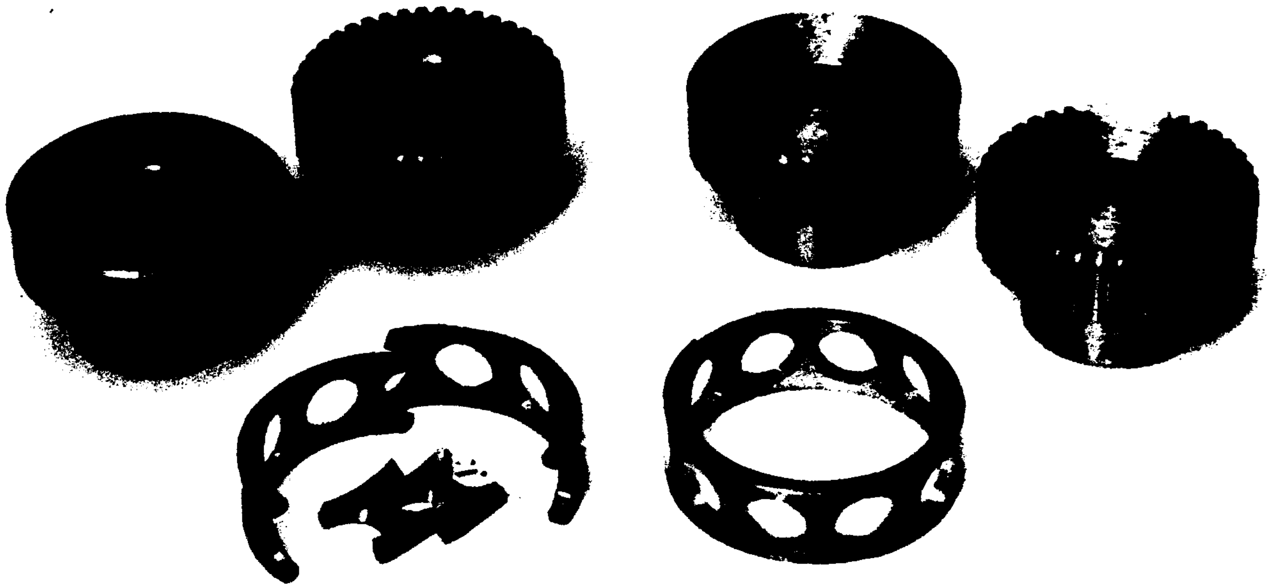


FIGURE 21 View of the Failed "Shock Compacted" Components

TABLE 5.
Matrix of Test Samples.

Material	Cages	Gears	Brushes	Bushings
As-Cast Material				
50/50	M	M	M	M
75/25	M	M	M	M
90/10	M	M	M	M
Shock Compacted				
50-50 -325 mesh	**			
50/50 -100+325 mesh	F	F	M	M
75/25 -325 mesh		F		M
75/25 -100+325 mesh	F	F	M	M
90/10 -325 mesh		F		M
90/10 -100+325 mesh	F	F	M	M
Hot Isostatic Pressed				
50/50 -325 mesh	M	M	M	M
50/50 -100+325 mesh				M
75/25 -325 mesh	M	M	M	M
75/25 -100+325 mesh				M
90/10 -325 mesh	M	M	M	M
90/10 -100+325 mesh				M

M Manufactured.
F Attempted to manufacture, material too brittle
** Material unsuccessful

preparations for testing. This probably occurred due to the internal stresses developed during consolidation (shock compaction) that were relieved during manufacturing operations.

5.1 Component Testing.

Standard in vacuum test facilities available at NCT were used to test the components by examining their torque performance. Such information provides an indication of the overall endurance of the component. The extensive tribological testing performed by NCT in the past on a wide variety of materials was the basis for the selection of the test conditions in this program. This also facilitated direct correlation with existing data. All testing was performed at ambient temperature (20°C +/- 2°C controlled in the laboratory) using calibrated instruments and power supplies. For the cages, bushings and gears the data was acquired on a chart recorder, in line with previous testing at NCT. The brush test measurements were taken using a Solartron Type 7066 computing digital voltmeter for the 100mv range and the time period of these measurements, had an accuracy of ± 0.001%.

5.1.1. Cages.

The National Centre of Tribology developed the use of ion plated lead films as a lubricant with a high load carrying capacity for spacecraft components as early as 1972. These films have a limited ability to operate under atmospheric conditions, currently a distinct advantage over some of the more exotic MoS_2 coatings. When applied to rolling element bearings, a lead bronze cage is additionally employed. One of the functions of this cage is to transfer lead bronze via the balls to the race, thus replenishing the lead film. However, with the increasing life and speed requirements of the space industry limitations are now being set by the cage behavior; in particular the formation of wear particles.

Early research [19] showed that a continuously cast lead bronze, of approximately 10% lead, was the optimum choice based on a bearing duty of two million revolutions. This research also examined some of the factors which affected the transfer rate and the subsequent torque noise registered by bearings fitted with lead bronze cages.

Since this early research [19 - 20], limitations have started to appear in the performance of these lead bronze cage materials. The performance of the bearings has always been susceptible to wear of the cage and subsequently induced noise. In situations, where extended life was required ($> 10^8$ revolutions) cage wear was significant and where variations in speed occurred, cage inertia effects contributed to increased debris generation.

The bearing test rig, and a cross section through the facility are shown in Figures (22-23). Each pair of cages were fitted to bearings whose races had been lead ion plated in accordance with standard NCT practice. The test bearings were purchased from SNFA, and were of angular contact type ED20 to ABEC7 standard in AISI 52100 material. Other bearing parameters are shown in Table 6.

TABLE 6.

ED20 Bearing Size Parameters.

Outer Diameter	42 mm
Inner Diameter	20 mm
Bearing Width	12 mm
Ball Size	7.14 mm
Ball Complement	10
Contact Angle	15°
Bearing Conformity	1.14

FIGURE 22 View of the Bearing Test Facility

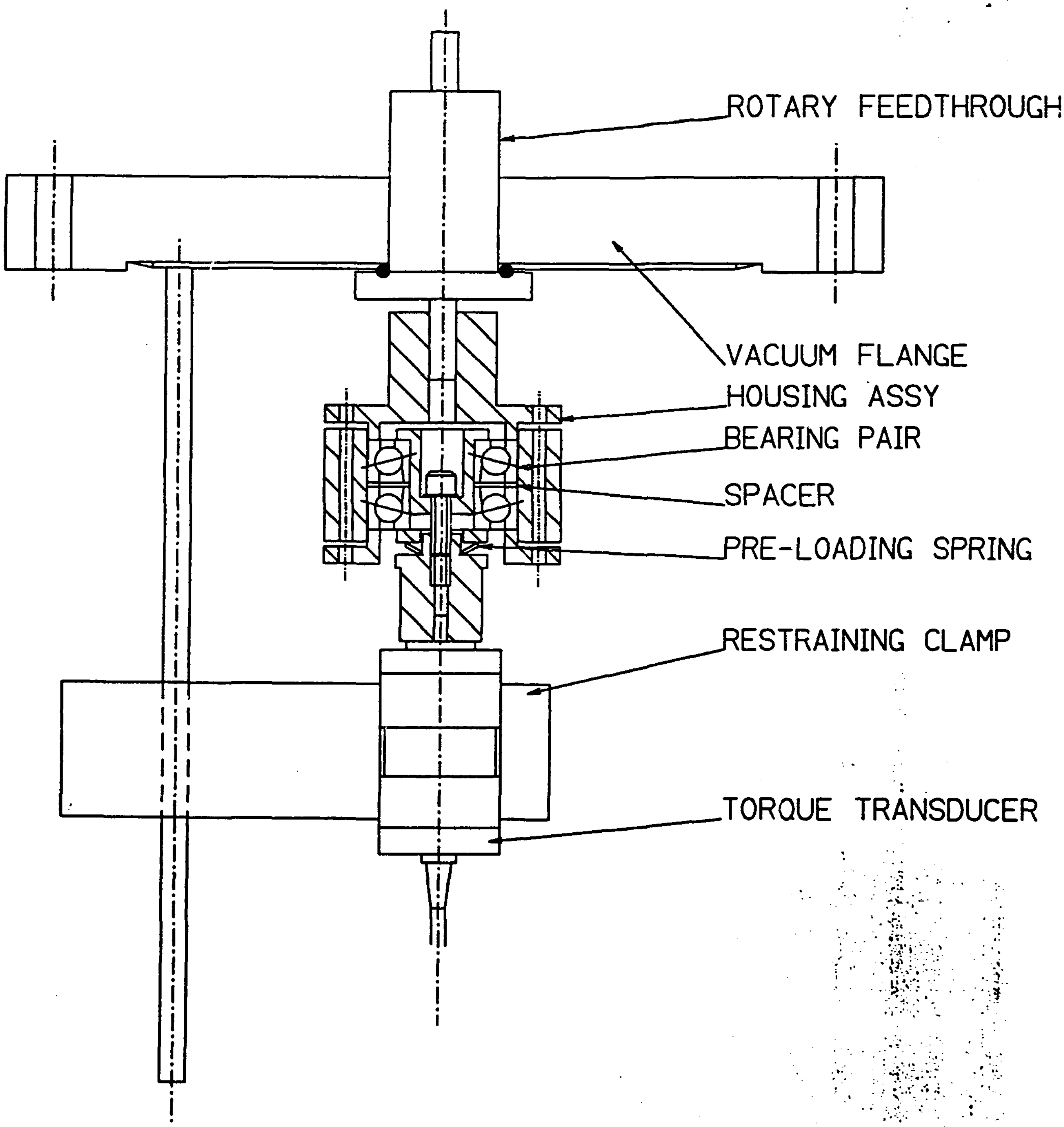


FIGURE 23 Cross section drawings of the in-vacuo bearing torque measurement system

Each test involved a pair of bearings, with a "soft" preload of 40 N set by the deflection of the wavy washer. The bearings were rotated at 100 rpm for 2×10^6 revs, at test pressures between 10^{-6} and 10^{-8} torr. The average torque and the peak torque noise levels were sensed by an inductive torque transducer and the signals were fed to a chart recorder.

The bearing torque test results for the different alloys and manufacturing methods are shown in Figures 24 and 25. Figures 24-D and 25-D illustrate the results from a standard lead bronze caged pair of bearings. Since all the materials tested can be expected to have similar coefficients of friction in this mode of operation, the mean torque level for the bearings should be similar in each case if the preload setting was applied correctly. The recorded mean torque levels of 20 gm.cm, were the same in all the tests, confirming that correct preload settings had been maintained.

The torque noise generated by the bearings is of importance in comparison to other cage materials. Short lived torque spikes were evident for all the materials. All the cage materials produced from the supersaturated lead copper alloys performed better than the lead bronze for short periods, unfortunately at other times the torque spikes generated by material transfer from the cage were of a high magnitude. As can be seen in Figure 24-D and 25-D, the peak torque noise levels for bearings fitted with standard lead-bronze cages varies between 50 and 100 gm.cm. over the duration of the two million revolutions. The key observations from our tests include:

- Peak noise levels increased with an increase in the lead content.
- 50/50 "As-Cast" exhibited dramatic increases in peak torque levels as the test progressed. This is probably due to the transfer of large copper particles from the cage (Figure 24-A).
- 75/25 "As-Cast" had a performance very close to that of the standard lead bronze (Figure 24-B).

- 90-10 "As-Cast" exhibited a better performance than the standard lead bronze cage with the exception of a number of short time periods (Figure 24-C).
- 50/50 and 75/25 "HIP'ped" cages registered high torque glitches periodically throughout their tests, although the magnitude of these fell as the tests proceeded (Figure 25-A,B).
- 90/10 "HIP'ped" material initially exhibited very low torque noise but this rose periodically as the test proceeded, presumably with transfer of material to the raceways following extended running (Figure 25-C).

A segment of the time plot taken from the 90/10 "HIP'ped" results, at the inception of the first major noise area around 1.2 million revolutions shows relatively high value torque spikes at random positions on the trace (Figure 26). As the test progressed, the regularity and severity of these peaks increased, but the baseline torque noise levels stayed low.

SEM examination of the cages after testing did not provide conclusive results on the mechanisms for failure. In the case of the 90/10 "HIP'ped" sample that provided the best performance, examination of the inner race and the cage ball pockets reveals only light wear marks, and the ball track on the inner race shows only a small amount of transfer at the edges (Figure 27).

The 50/50 "HIP'ped" sample showed the worst performance, and examination of its inner race and cage pockets reveals wear marks that were darkened heavily compared to the 90/10 "HIP'ped" sample. Substantial amount of wear debris was also present to the side of the ball track on the inner race (Figure 28).

5.1.2. Gears.

Gears are widely used in space satellites for the generation of high torque capacity when using low torque capacity prime movers. The basic design of gears for use in space is as on earth,

Figure 24-A
Bearing Cage Performance
50/50 As Cast Material

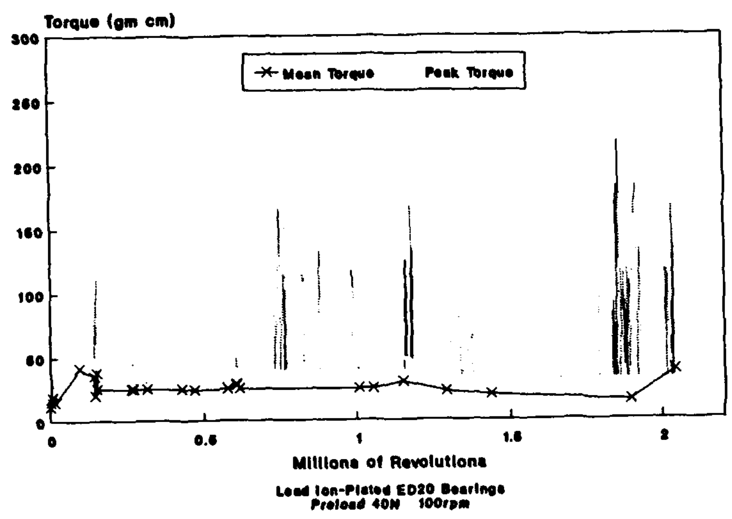


Figure 24-B
Bearing Cage Performance
75/25 As Cast Material

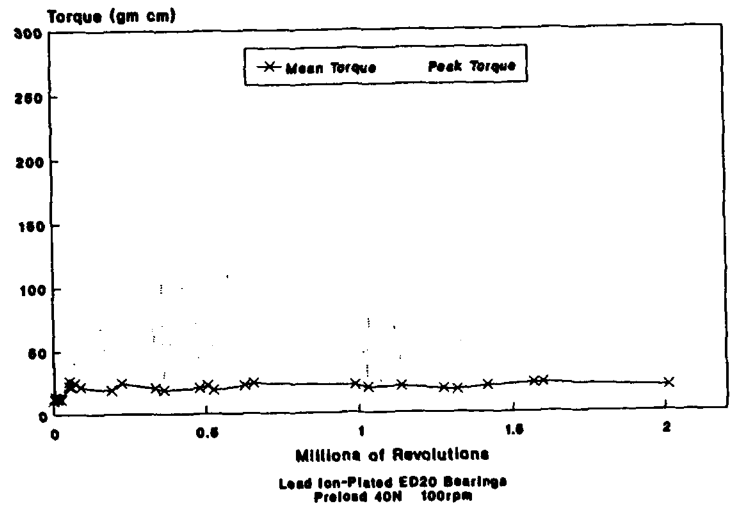


Figure 24-C
Bearing Cage Performance
90/10 As Cast Material

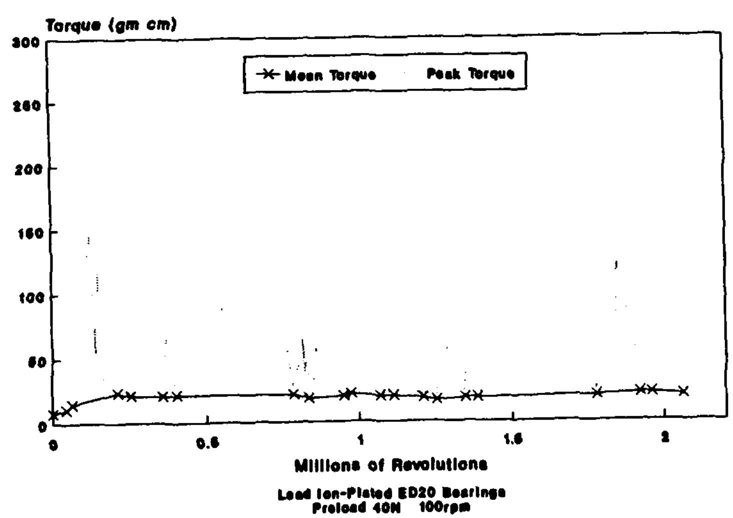


Figure 24-D
Bearing Cage Performance
Standard Lead-Bronze Cages

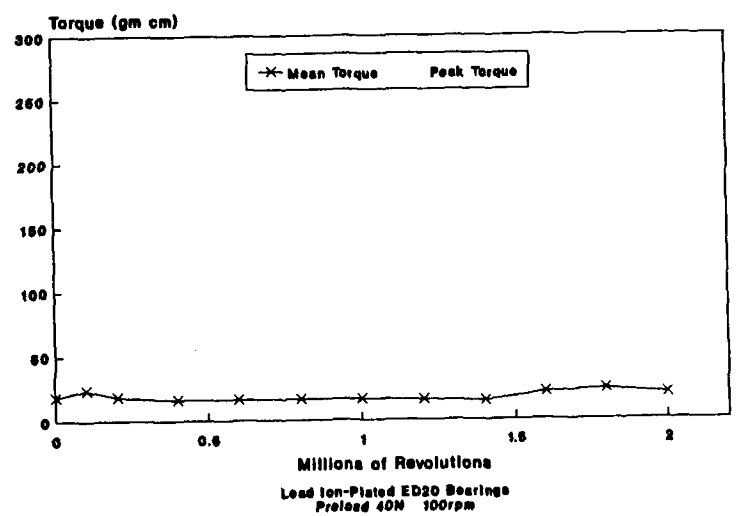


FIGURE 24 Bearing Cage Test results of the "As Cast" material

Figure 25-A
Bearing Cage Performance
50/50 -325 mesh HIP'ed Material

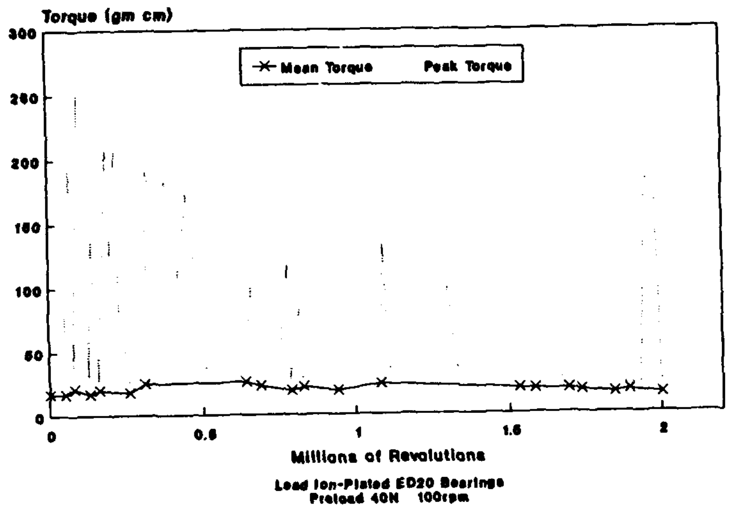


Figure 25-B
Bearing Cage Performance
75/25 -325 mesh HIP'ed Material

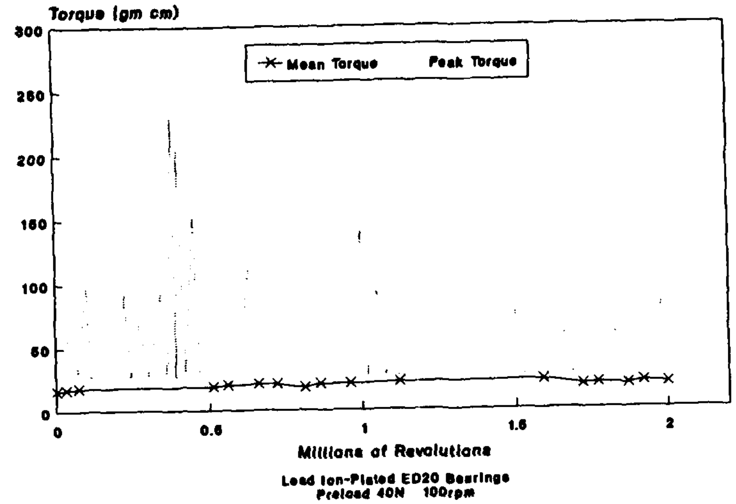


Figure 25-C
Bearing Cage Performance
90/10 -325 mesh HIP'ed Material

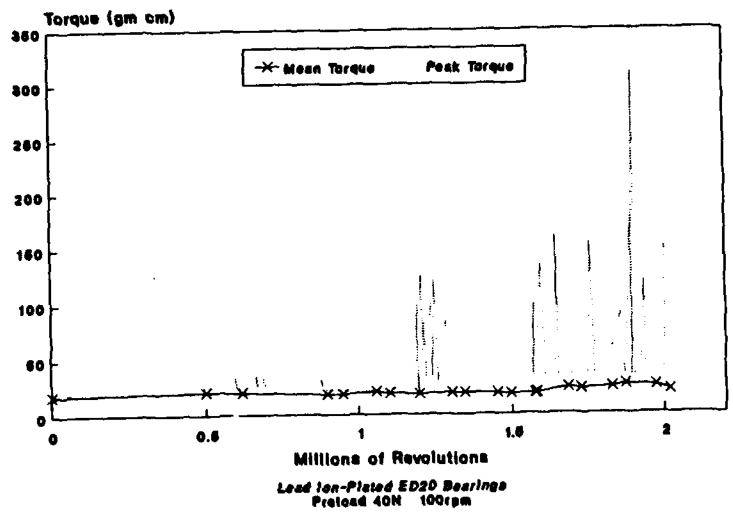


Figure 25D
Bearing Cage Performance
Standard Lead-Bronze Cages

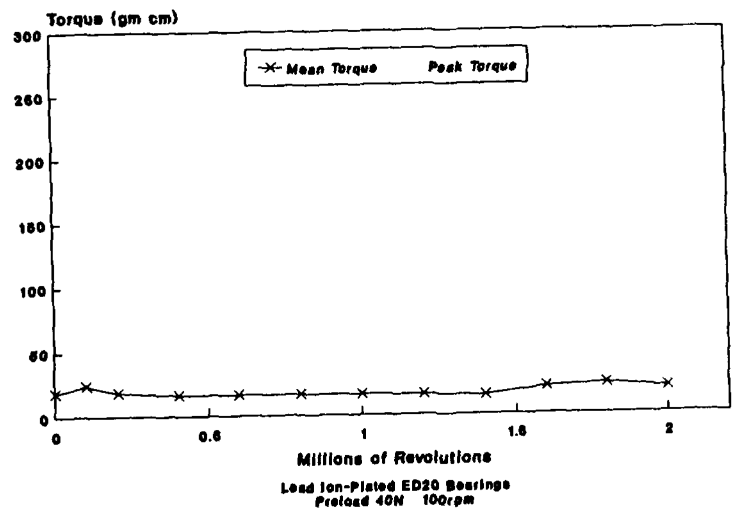


FIGURE 25 . Bearing Cage Test results of "HIP'ped" -325 Mesh material

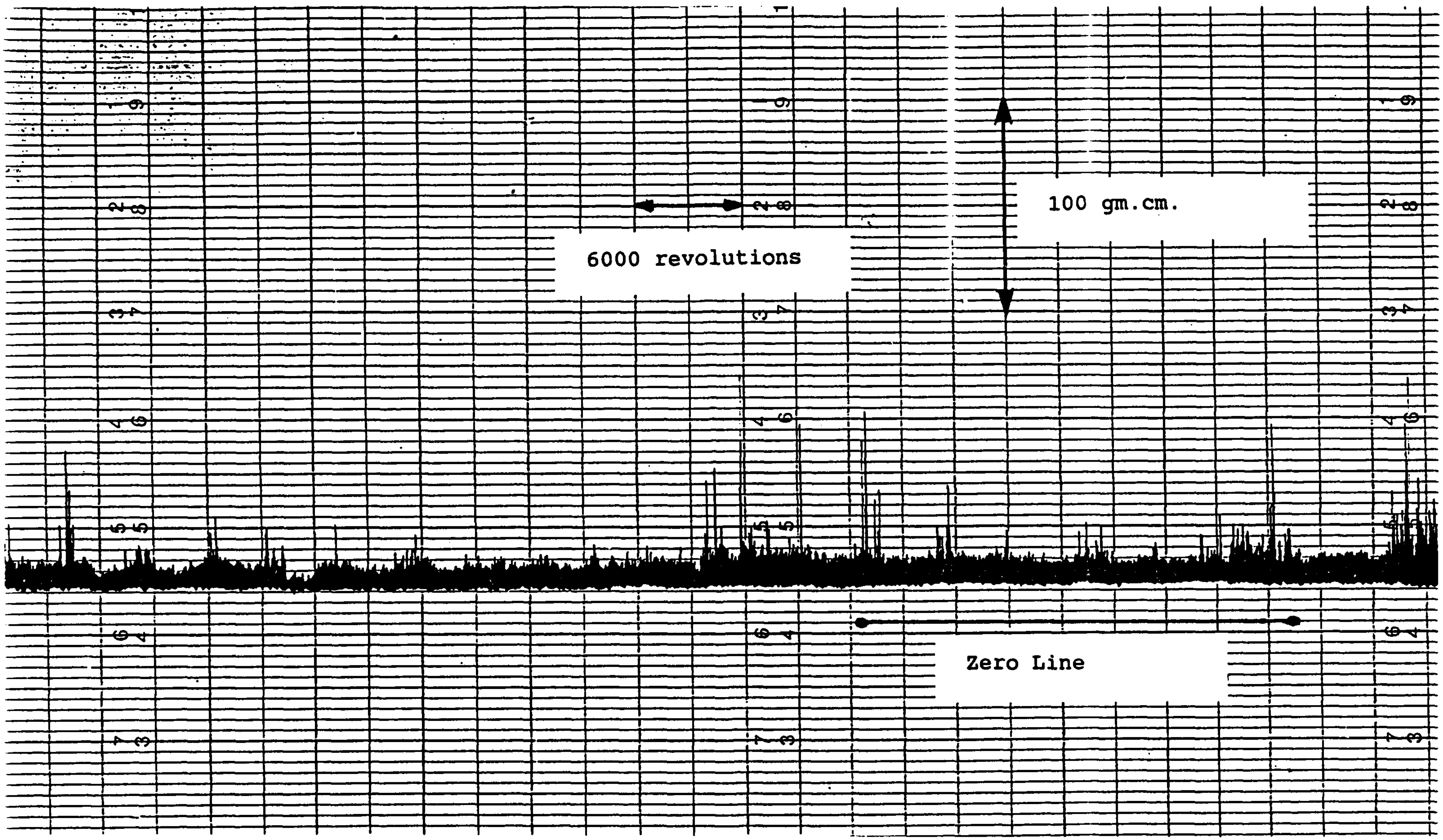


FIGURE 26 Plot of Time Versus Torque of 90.10 "HIP'ped" Cage

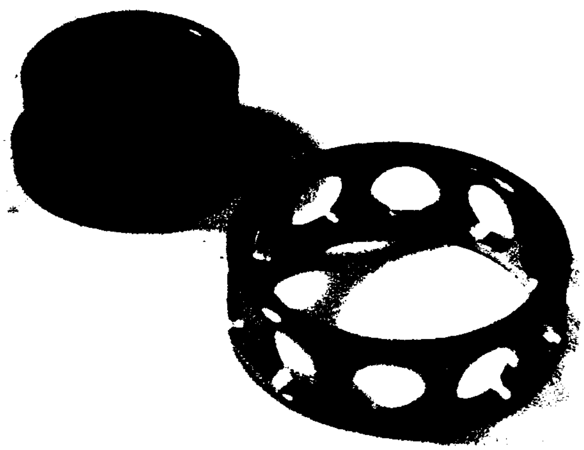


FIGURE 27 View of 90/10 "HIP'ped" cage and its Test Bearing Inner Race

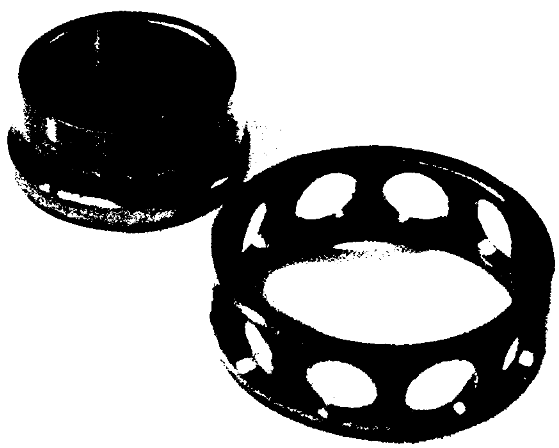


FIGURE 28 View of the 50/50 "HIP'ped" cage and its Test Bearing Inner Race

the major design problem is to minimize mass while ensuring load carrying capacity, and to choose a lubrication system which is compatible with the space environment for up to ten year life durations or longer. The choice of gear materials, and some historical data for direct comparison with the results obtained in this series of tests are provided in Reference 21.

To date, self-lubricating gears in space applications have been limited to polymeric materials and the standard bronze materials [21]. Conventionally these have been employed in low contact stress applications (typically <20 MPa). Medium stress applications (typically 100 MPa) for dry lubricated gears, where contamination by fluid lubricants could not be tolerated, have employed gears plated with films such as lead or gold. Such films always have a limited life.

A photograph of the four-square gear test rig is shown in Figure 29. The rig was underslung by the stub shaft from a heavy duty ferrofluidic rotary feedthrough, and driven by an external drive motor. The steady at the lower end of the rig maintains stability. The gear preload was locked into the system by rotating the lower gearwheel, against the spring load, around the shaft and locking in position. After initial trial testing, a load of 2 N/mm face width (on the gear teeth) was chosen for comparison purposes. The running torque of the gears was measured via the linkage arm, which prevented the main body assembly from rotating.

The gear module used was 0.75 mm, and the pinions manufactured from the various alloys had 41 teeth and a face width of 10 mm. For the purposes of these tests, the counterface gearwheels were manufactured from nitrided steel (hardened to 1000 HV) and had 120 teeth of 3 mm face width. All the gears were manufactured to British Standards-BS 978 Part 1 - Class C (approximately equivalent to AGMA 9). All tests were performed under vacuum, at pressures between 10^{-6} and 10^{-7} torr, for one million revolutions at 100 rpm and the torque levels were continuously monitored using a chart recorder.

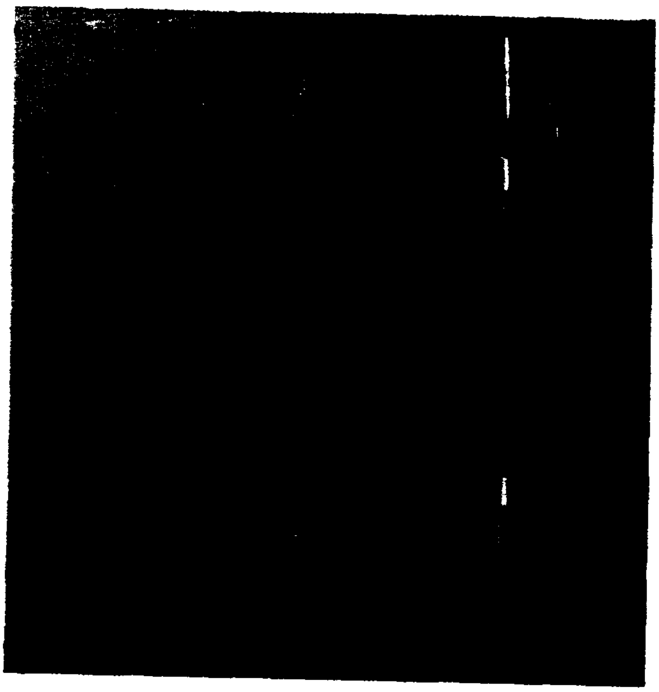


FIGURE 29 View of the Four Square Gear Test Facility

The mean torque and torque noise (defined as the half width of the torque signal), for each of the six materials tested is shown in Figures 30 and 31. No gears were tested from the "Shock Compacted" samples as they had failed prior to testing by cracking along the teeth or in the blank as described in an earlier section. For the bearings, the friction levels can be expected to be similar in all cases and hence the mean torque levels should be of the same order of magnitude, assuming that the preload setting was correct. After a brief running-in period, the mean torques were similar, about 20 gm.cm., and remained constant throughout each test. However, the torque noise was different in each case. The specific observation include:

- For both the "As Cast" and the "HIP'ped" gears the torque noise increased with increasing lead content,
- The "As Cast" 50/50 gear registered the worst torque noise of all the six materials tested in this program
- In general, the "HIP'ped" materials provided less torque noise than the "As Cast" materials. The 90/10 "HIP'ped" gears provided the most superior results.

Except for the "HIP'ped" 50/50 material, the gears were weighed before and after testing. The greatest weight losses were from the "HIP'ped" 90/10 material, amounting to approximately 0.1% weight loss from an initial gear weight of 95 grams. However, there was no consistent relationship between weight loss and material type, and it is difficult to draw any significant conclusions from these results.

On completion of the gear tests, the mean tooth wear was measured by surface profilometry. The average depth of the wear scars on each type of material was calculated, and divided by the number of tooth encounters to give a mean wear rate per tooth encounter. The results are as shown in Table 7.

Figure 30-A
Gear Performance
50/50 As Cast Material

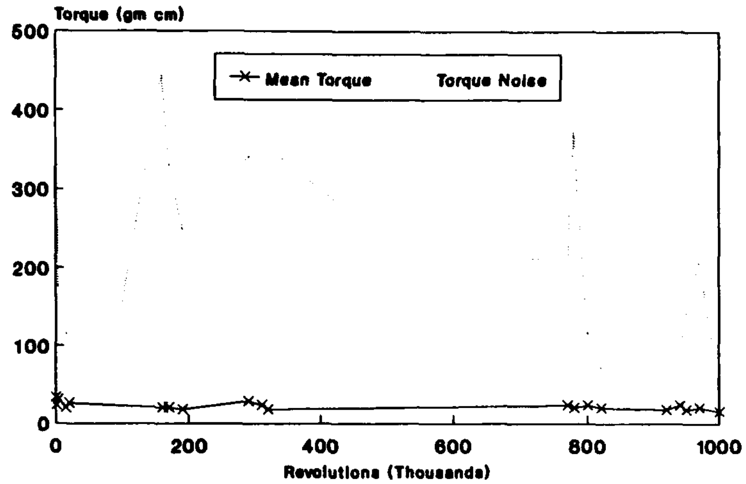


Figure 30-B
Gear Performance
75/25 As Cast Material

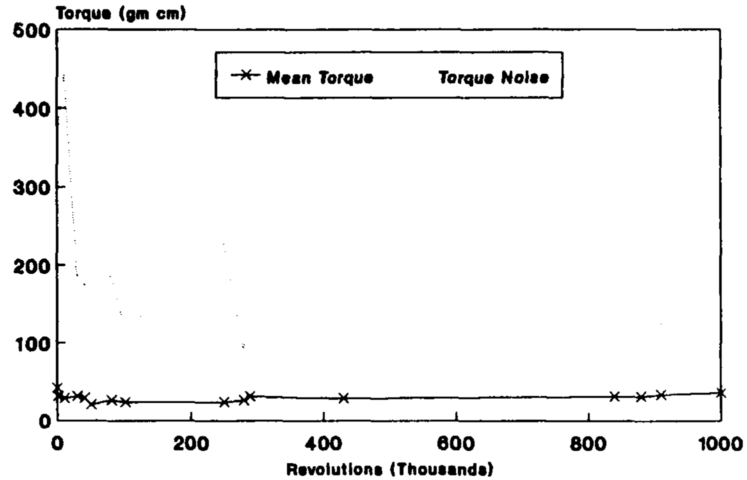


Figure 30-C
Gear Performance
90/10 As Cast Material

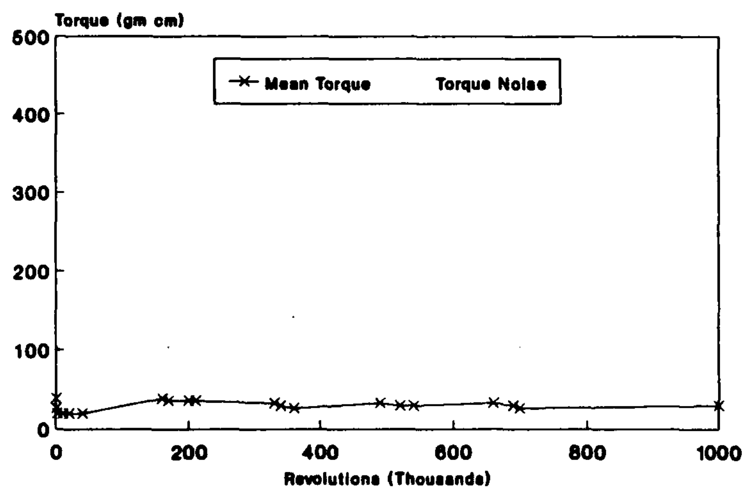


FIGURE 30 Gear Test results of the "As Cast" material

Figure 31-A
Gear Performance
50/50 -325 mesh HIPped Material

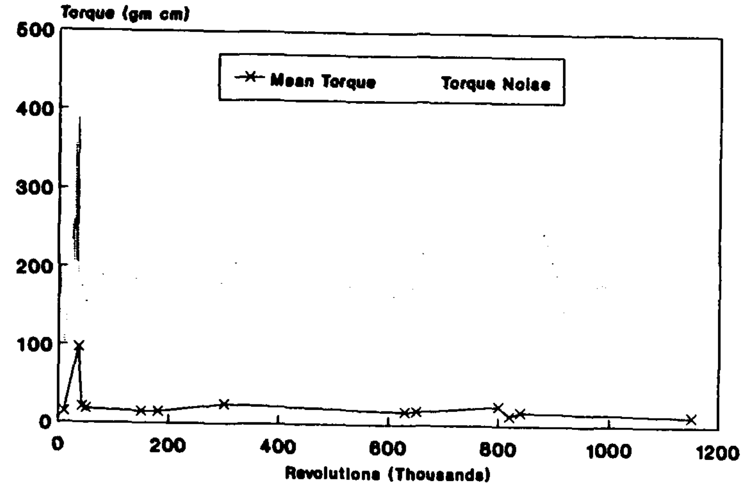


Figure 31-B
Gear Performance
75/25 -325 mesh HIPped Material

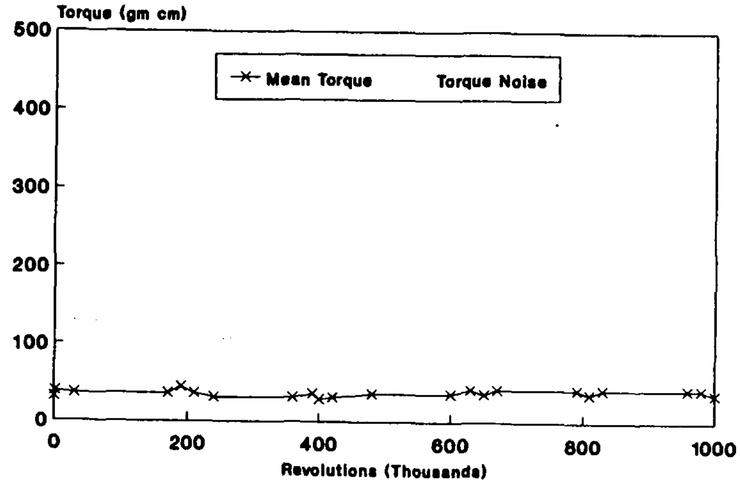


Figure 31-C
Gear Performance
90/10 -325 mesh HIP'ed Material

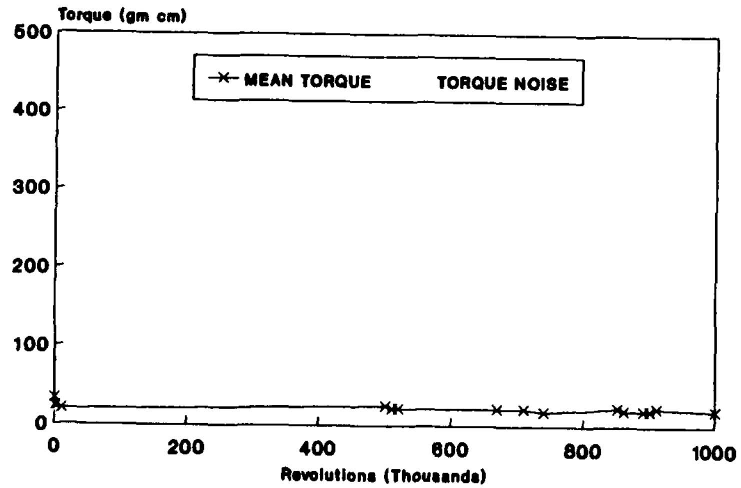


FIGURE 31 Gear Test results of the "HIP'ped" -325 Mesh material

TABLE 7. Gear Wear Rate Measurements

Material Mean Wear Rate (mm/tooth encounter x 10^{-8})		
Material	As Cast	"HIP'ped"
90-10	2.2	6.8
75-25	0.93	1.5
50-50	1.0	2.1

These results confirm the weight loss measurements, indicating that the greatest wear rates were obtained with the 90/10 "HIP'ped" material, which paradoxically gave the best torque measurements in terms of the torque noise. There were no significant differences between the wear rates of the other five materials.

A typical photograph of gears made from two different materials is shown in Figure 32. An even, consistent contact zone can be seen on both gears.

A close-up view of the 90/10 "As Cast" and the 90/10 "HIP'ped" gears is shown in Figures 33 and 34. The torque noise levels from these two gears were different as the "As Cast" alloy gear set showed a consistently noisier torque output. Comparison of the photographs shows a much more ragged edge to the wear zone of the "As Cast" alloy gear versus the "HIP'ped" gear.

SEM examinations performed on these two gear samples, illustrates that the "HIP'ped" gear shows a clean wear mark, while the "As Cast" gear has heavy smears of lead present and also a heavy debris presence at the edge of the gear (Figure 35). Similar observations were made in the case of the 50/50 copper lead alloy "As Cast" gears, which gave the highest torque noise values among all the gears tested in this program.

The 90/10 "HIP'ped" material performed the best of the materials tested when torque noise levels were considered, however its wear rate of nearly 7 x 10^{-8} mm per tooth encounter was very high. This alloy would undoubtedly be able to withstand higher

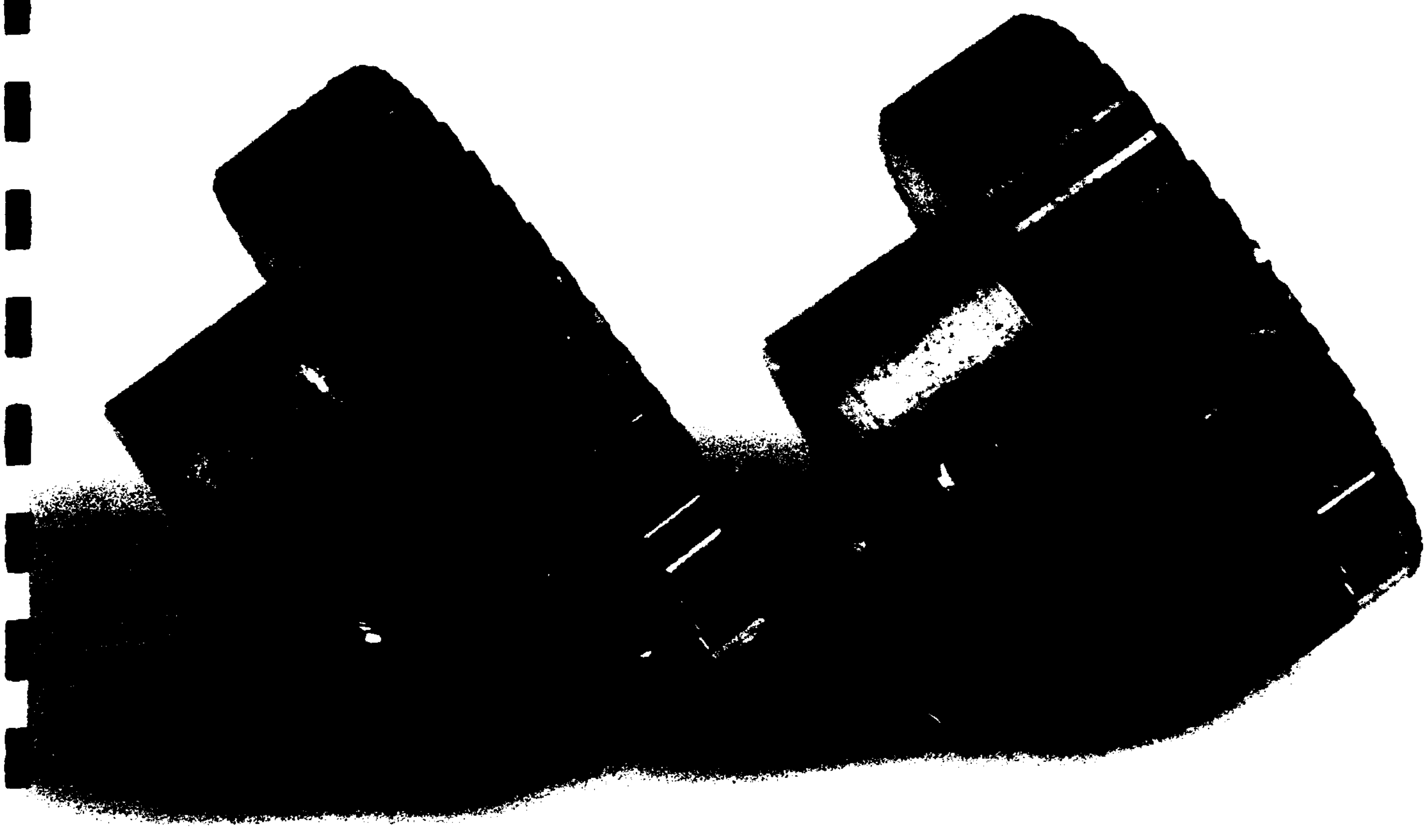


FIGURE 32 View of two types of "As Cast" Gears after Testing. Left: 50/50 Cu/Pb Right: 90/10 Cu/Pb

FIGURE 33 Close-up View of the 90/10 "As Cast" Gear after Testing

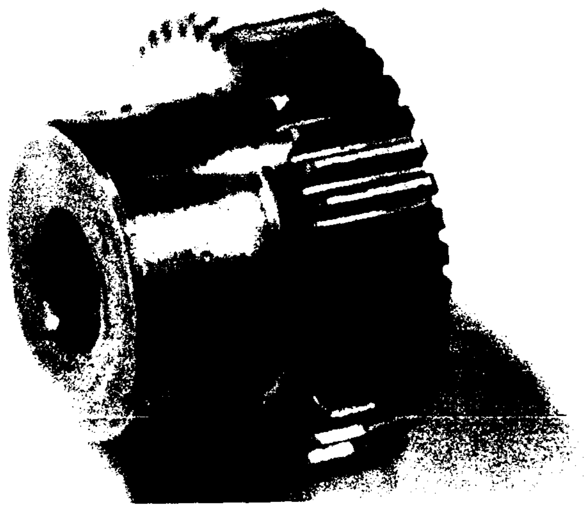


FIGURE 34 Close-up View of the 90/10 "HIP'ped" Gear after Testing

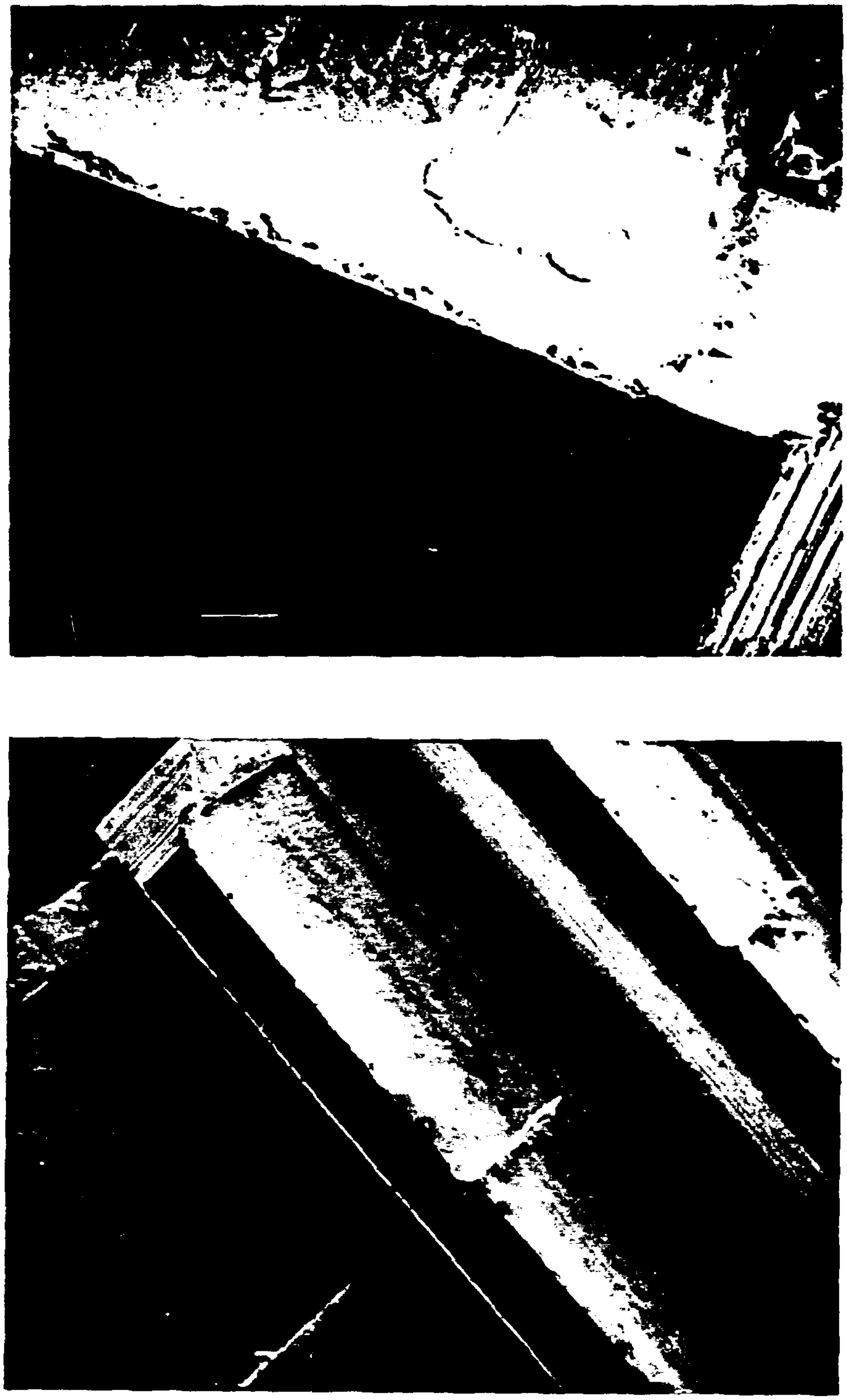


FIGURE 35 SEM Views of Gears after Testing Top:
Top: 90/10 Cu/Pb "As Cast"
Bottom: 90/10 Cu/Pb "HIP'ped"

contact loads, however the wear rate would increase commensurately. Comparison with wear rates for plastic gears running against stainless steel wheels show the plastics to have much lower wear rates at similar load capacities, example for Vespel SP3, a polyamide with MoS_2, the wear rate was 6×10^{-9} mm per encounter at a load of 7 N per mm of gear face width (See Ref 21, Table 8). The higher wear rates combined with the weight penalty of the copper-lead alloys suggest that future uses of these alloys in gears for space applications is unlikely.

5.1.3. Bushings

There are a limited number of applications in space for self lubricating bushings. These are normally in areas which do not see continual usage, and to date have employed the standard proprietary materials which are available from several manufacturers. There is little data available about the performance of bushings in vacuum. Reference 22 by Poncet provides some general data, and it was on the basis of this paper that the test conditions were chosen for this program. Previous experience at NCT has not been published in the open literature and is limited to tests at contact loads ten times higher than those used in this program.

A typical rig is shown in Figures 36 and 37. The rig is underslung from a heavy duty ferrofluidic rotary feedthrough and driven by a motor/oscillatory crank mechanism external to the vacuum chamber. The bush is clamped into the central lever arm, and is loaded against the stainless steel test shaft (typically 180 HV) by the stack of belleville washers seen in Figure 36. A load sensor on the opposing side, Figure 37, was used to set the load levels. The frictional torque generated is measured by the load cell, which supplies the torque required to restrain the free-swinging test section. All opposing shafts were manufactured from 316 stainless steel to a surface finish of 0.4 microns CLA. The bush hole diameter was nominally 20 mm with clearance toleranced between 0.01-0.05 mm.

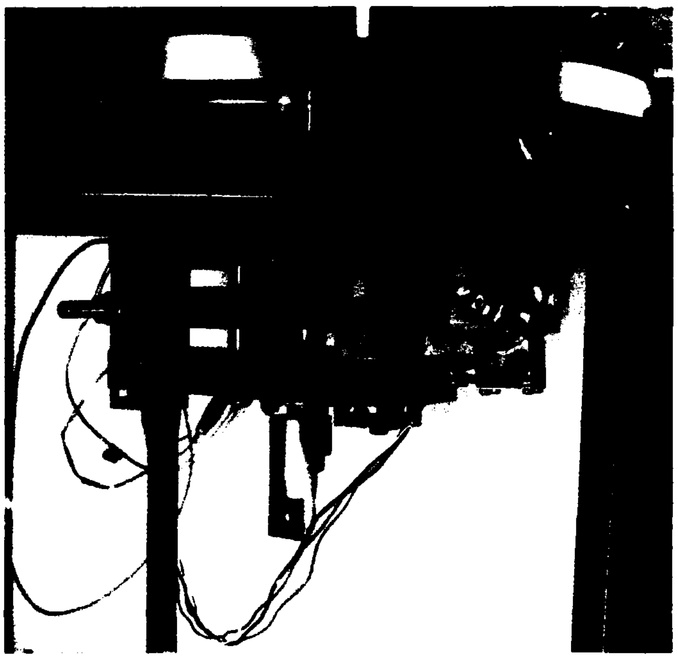


FIGURE 36 View of the Bushing Test Rig with Torque Measuring Transducer to the right and Belleville Washers on the left

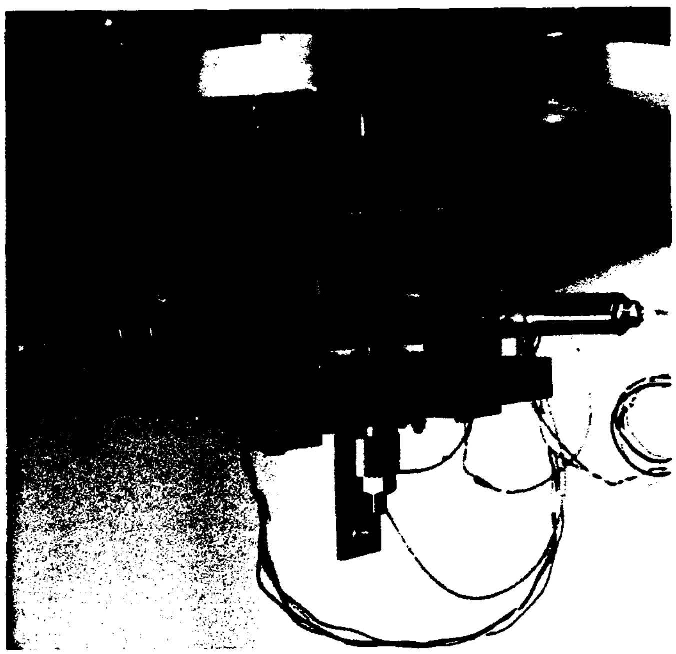


FIGURE 37 View of the Bushing Test Rig showing Applied Load Sensor in the Distance

After initial set-up trials, the 75/25 "As Cast" sample was run, under vacuum levels of 10^{-5} torr, for 4 x 10^4 oscillations of 50° degrees under a nominal load of 810 N at 60 rpm. These test conditions equate to a PV factor of 2.8E-2 N mm^{-2} m s^{-1}. Figure 38 shows the condition of the trial bush after testing. Note the transfer of material to the mating shaft. Despite running this test for four times longer than originally specified in the contract, no torque changes were apparent following the initial run-in period. It was decided therefore that all subsequent testing would be performed under identical conditions. A list of comments with regards to the condition of each of the tested samples is provided in Table 8.

A close examination of the torque characteristic (Figures 39-43) lead to the following general conclusions:

- The Shock Compacted material is generally unsuitable for this type of application.
- For all alloying constituents, the higher lead content achieves a more satisfactory performance.
- The best three performances were provided by the 50/50 "As Cast", the 50/50 -100+325 mesh Shock Compacted and the -100+325 mesh "HIP'ped" materials.
- The materials using the -325 mesh powder appear to release some copper during the run-in period, thus causing a transient torque perturbation.

A comparison of the 50/50 "As Cast" bushing sample with the 90/10 "As Cast" bushing after testing illustrates wear marks just visible inside the bush, and the transfer to the shaft is clearly visible (Figure 44). The 50/50 sample shows only lead transfer, while the 90/10 transfer includes traces of copper. Examination of the bores of the 50/50 "As Cast" and the 90/10 "HIP'ped" -325 mesh samples reveals that the smooth wear zone inside the 50/50 sample is very different from the pitted area inside the 90/10 sample, and explains the different behavior patterns seen during these tests

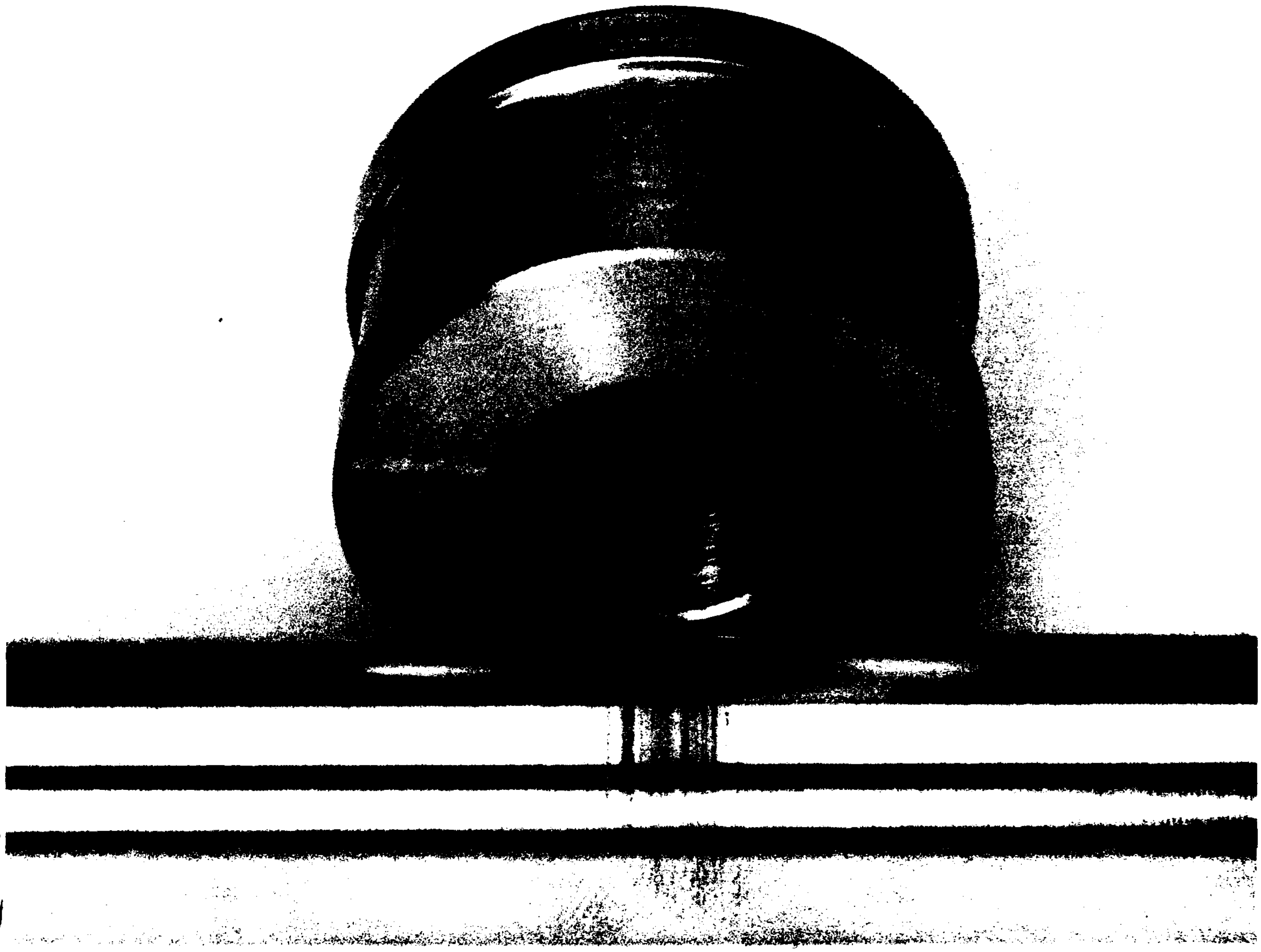


FIGURE 38 View of 75/25 "As Cast" Bush and Mating Shaft

Figure 39-A
Bushing Performance
50/50 As Cast Material

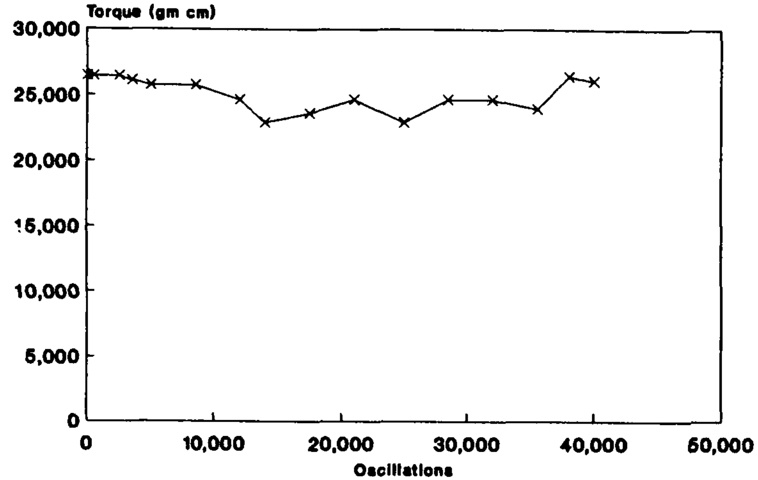


Figure 39-B
Bushing Performance
75/25 As Cast Material

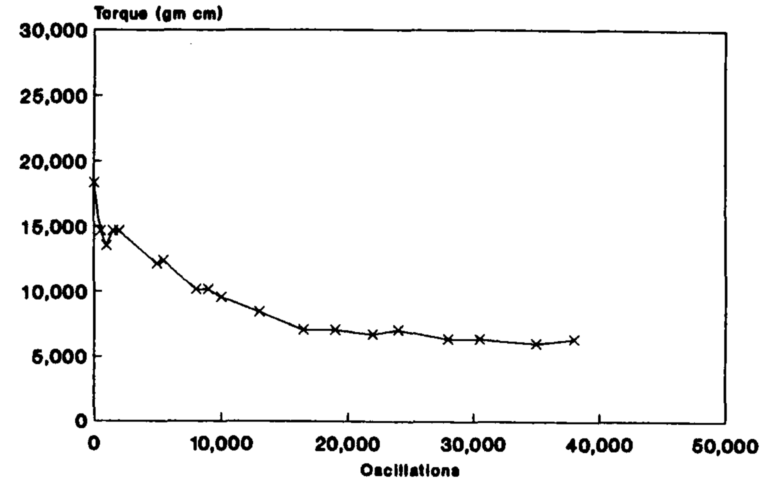


Figure 39-C
Bushing Performance
90/10 As Cast Material

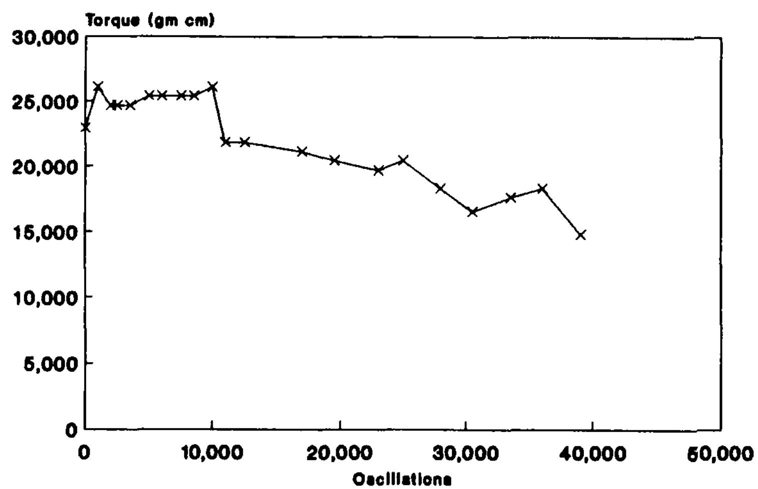


FIGURE 39 Bushing test results of the "As Cast" material

Figure 40-A
Bushing Performance
50/50 -100+325 mesh Shock Compacted

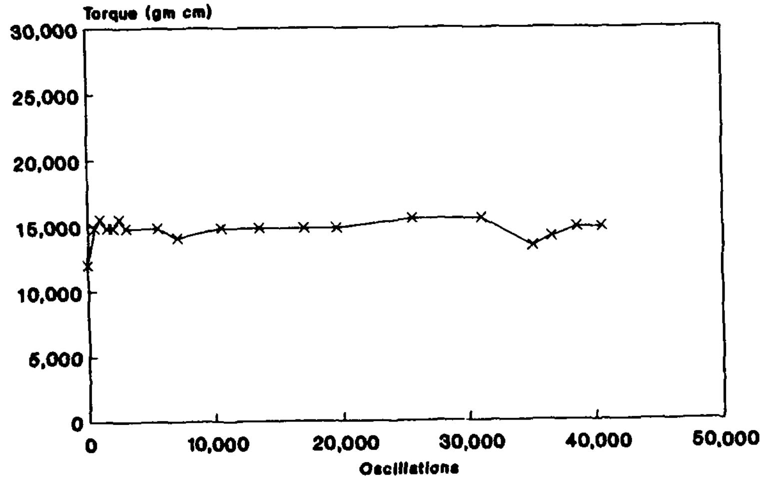


Figure 40-B
Bushing Performance
75/25 -100+325 mesh Shock Compacted

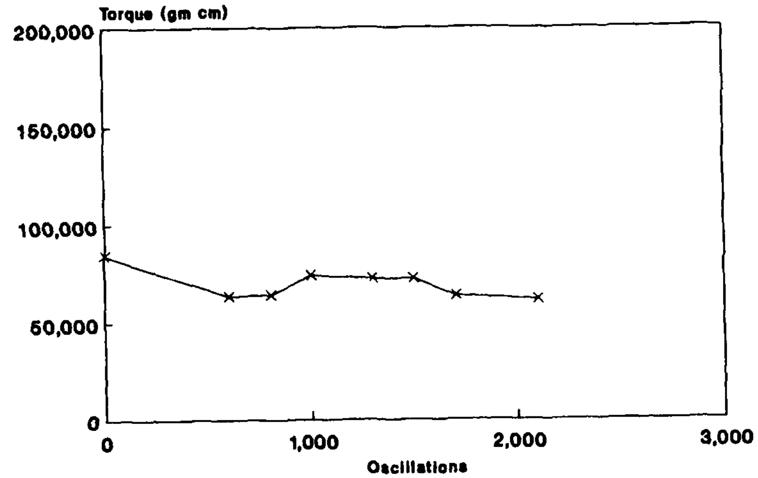


Figure 40-C
Bushing Performance
90/10 -100+325 mesh Shock Compacted

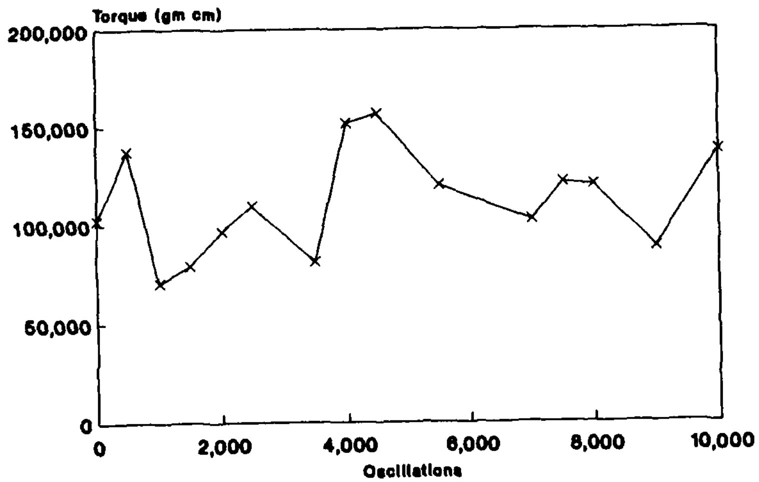


FIGURE 40 Bushing test results of the Shock Compacted -100 +325 material

Figure 41-B
Bushing Performance
75/25 -325 mesh Shock Compacted

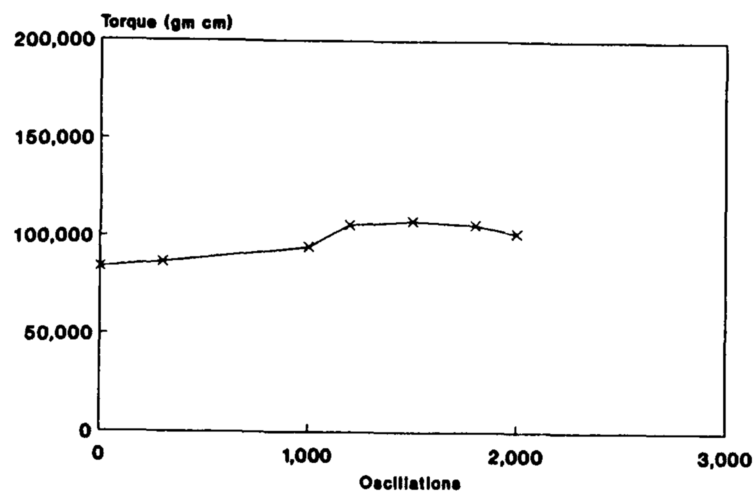


Figure 41-C
Bushing Performance
90/10 -325 mesh Shock Compacted

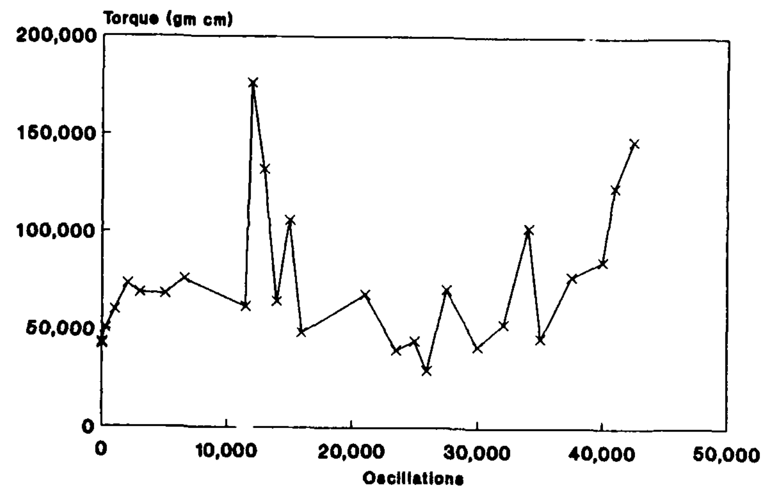


FIGURE 41 Bushing test results of the Shock Compacted -325 material

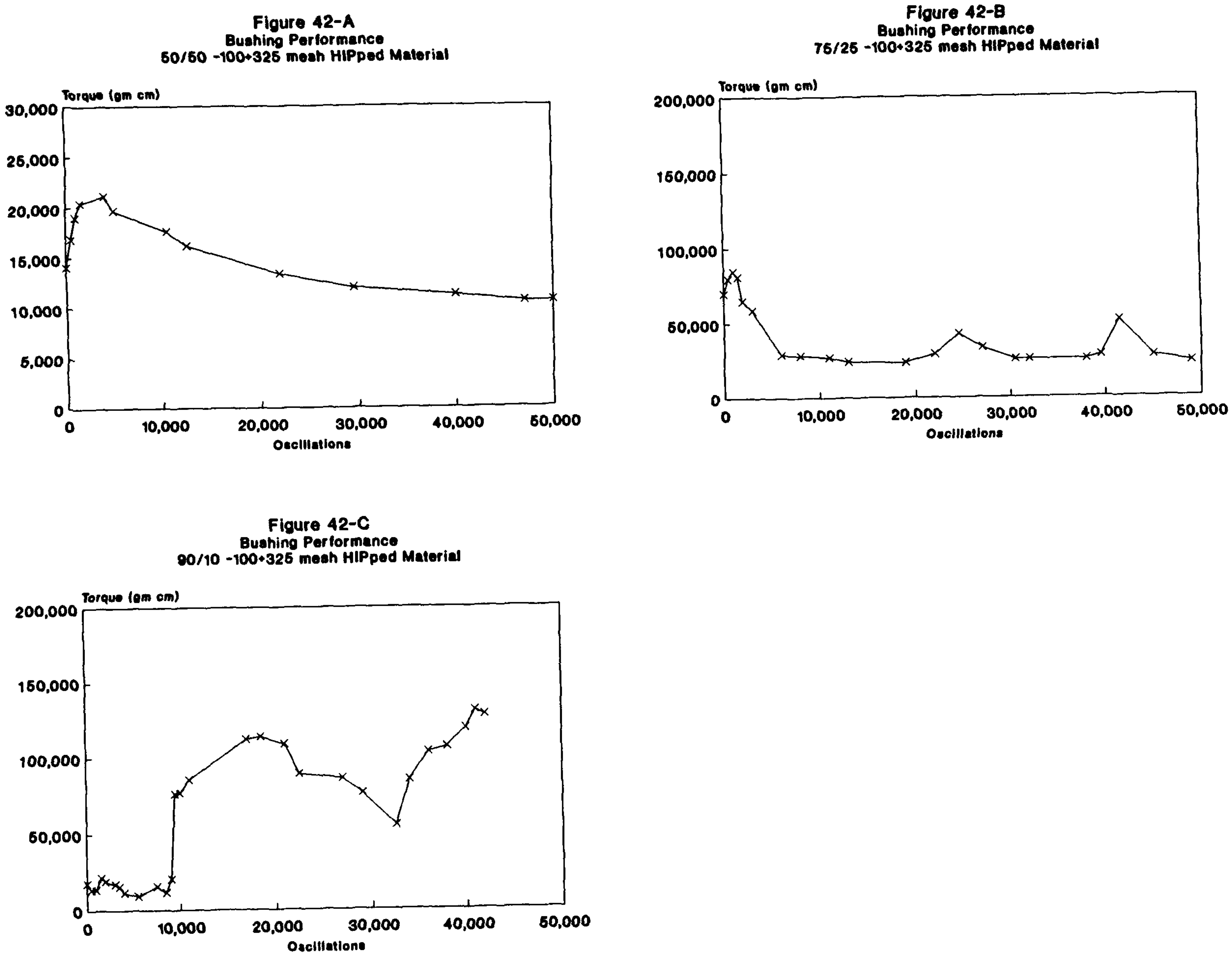


FIGURE 42 Bushing test results of the "HIP'ped" -100 + 325 material

Figure 43-A
Bushing Performance
50/50 -325 mesh HIPped Material

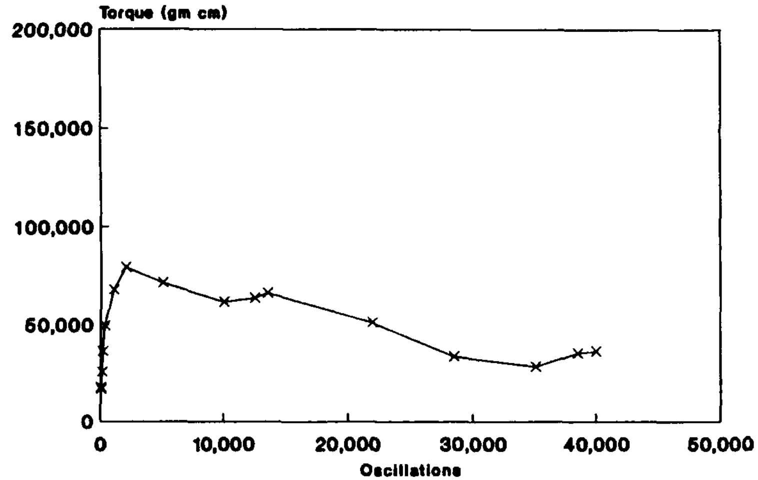


Figure 43-B
Bushing Performance
75/25 -325 mesh HIPped Material

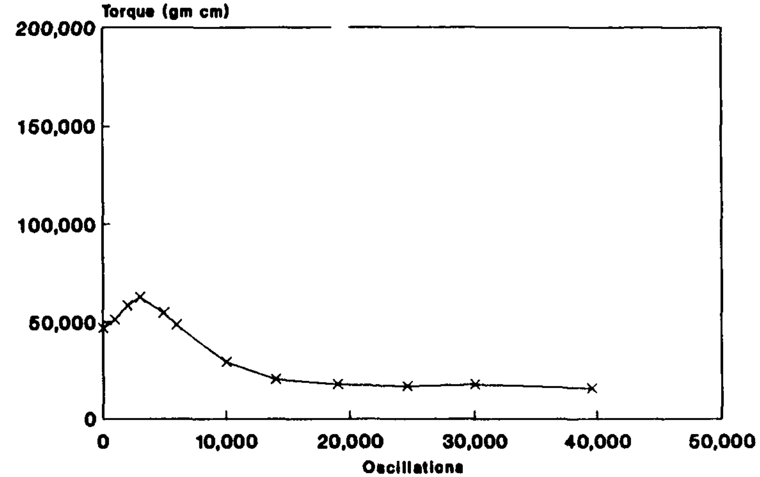


Figure 43-C
Bushing Performance
90/10 -325 mesh HIPped Material

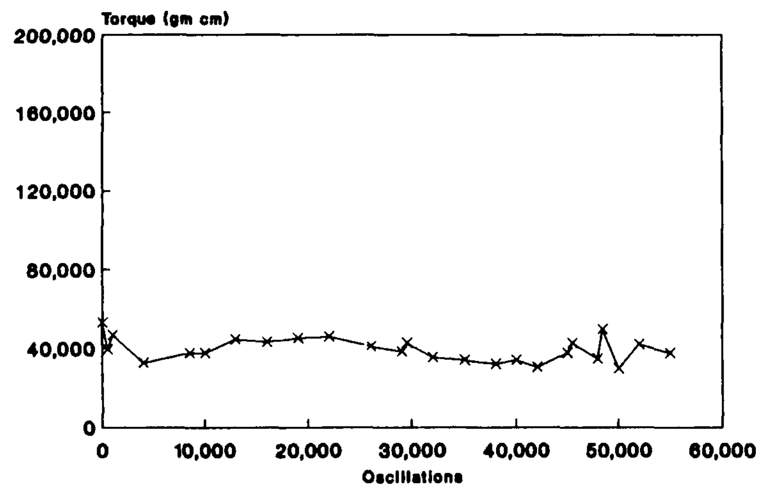


FIGURE 43 Bushing test results of the "HIP'ped" - 325 material

TABLE 8.
Bushing Test Results.

Material	Cycles	Comments
As-Cast		
50/50	40000	Torque consistent throughout, wear minimal, no obvious traces of copper
75/25	40700	Torque consistent throughout, wear minimal, some sign of copper transfer.
90/10	39218	Torque showed some short lived increases and recoveries throughout, although mean level gradually reduced. At stages the test squeaked noisily. Wear minimal, but copper transfer.
Shock Compacted		
50/50 -100 +325	40527	Torque consistent throughout. Wear minimal, no obvious copper transfer.
75/25 -325	2000	Torque levels very high. On removal,sections of bushing had broken away in two places. Heavy transfer to the shaft with copper present.
75/25 -100 + 325	2125	Torques very high, seized drive motor. Part of bushing broken away.
90/10 -325	41423	Torque levels high and variable throughout. Heavy transfer of copper and lead. The bushing disintegrated when separated from the shaft.
90/10 -100 + 325	9772	Variable high torque values. A large section of bushing had broken away and bushing is still seized to the shaft!
"HIP'ped"		
50/50 -325	40000	Torque increased rapidly at start, before falling back. A heavy transfer of lead to the shaft was noted, with no signs of copper presence.
50/50 -100 +325	50705	Torques consistent throughout. A heavy transfer of lead to shaft was noted, with no sign of copper transfer.
75/25 -325	39737	Torque levels rose initially, but settled back after 14,000 cycles. Transfer of lead to the shaft, with slight copper traces visible.
75/25 -100 +325	49134	Torque behavior extremely erratic, starting very high but falling back to normal levels, with tow further increases over the course of the test. A heavy wear transfer scar with copper present was noted on removal.
90/10 -325	55301	Torque behavior erratic and at high level. Wear scar did not show any heavy visible copper presence.
90/10 -100 + 325	42169	Torque increased many fold after about 10,000 cycles. On removal the bush had seized to the shaft!

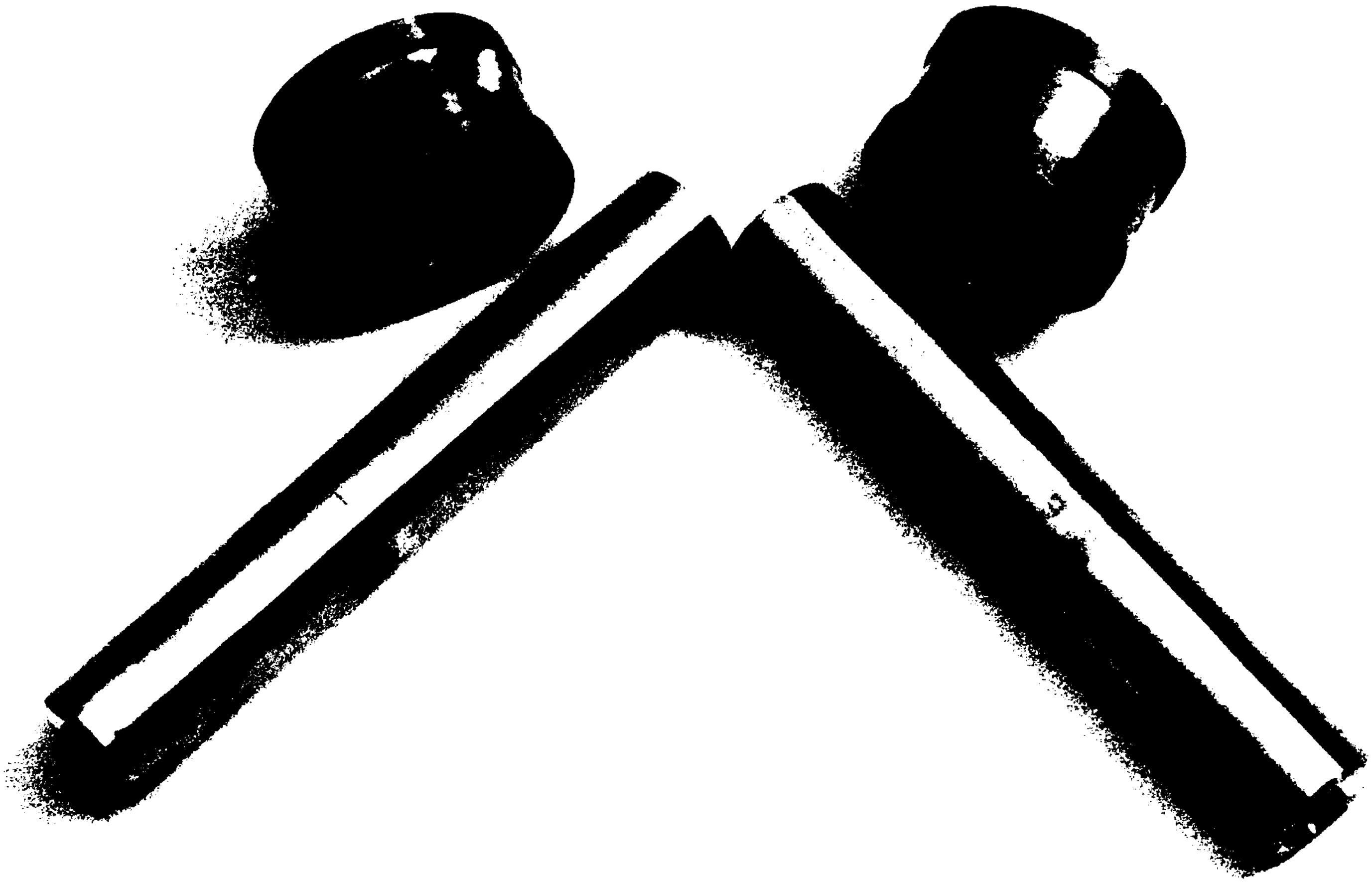


Figure 44 View of 90/10 & 50/50 "As Cast" Bushings and their Mating Shafts

(Figure 45). These observations are typical of the transfer patterns seen for all the other samples in this program.

On the basis of the catastrophic failures seen with some of the other shock compacted materials, the choice for further consideration resides between the "As Cast" and "HIP'ped" -100+325 mesh 50/50 materials. Since a torque load of 20,000 gm.cm. is equivalent to a friction coefficient of 0.24, it can be seen by reviewing Table 7 in Reference 22 that the "HIP'ped" material compares to the Glacier DU material.

Since bushings are usually produced by sintering, the copper-lead material in the powder form may very well be suitable for more extensive testing, dependent of course on the envisaged cost of production of such bushings versus the industry wide accepted standard Glacier DU manufactured by Glacier Metal, U.K..

5.1.4. Brushes.

Current pressed MoS_2/Cu/Si composite brushes used for electrical communication have limitations in terms of their electrical noise and wear - particularly for low earth orbit applications. NCT has tested several methods for brushes [23]. The problems with brushes currently in use in space mechanisms with regard to their susceptibility to contamination and the subsequent effects on their electrical performance is summarized in Reference 24. These materials can also cause small regions of high resistance on the opposing slip-ring, while the surface of the slip-ring (usually silver or gold plated) can suffer from tarnishing, which leads to higher contact resistances.

The small brushes were soldered to beryllium copper cantilever springs and pressed into contact with silver coated slip rings of 25mm diameter. An overall view of the slipping test facility and a close up view of the brushes in contact with the slip-ring is shown in Figures 46 and 47.

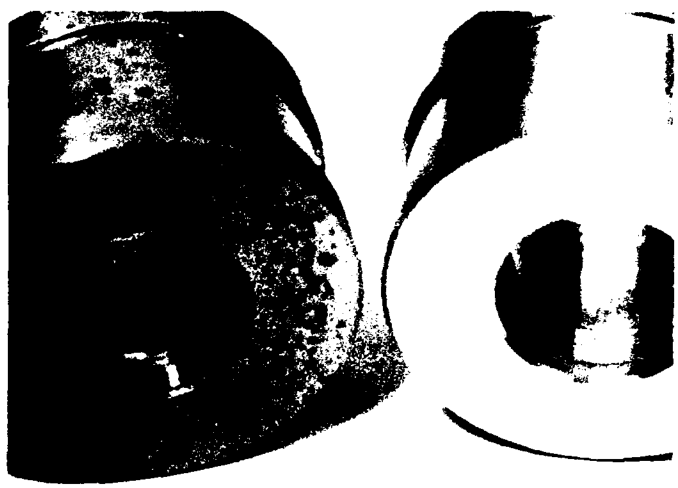


Figure 45 Close-up View of the Bor :s of Bushing After Testing Left: 50/50 As Cast, Right: 90/10 "HIP'ped" -325 mesh

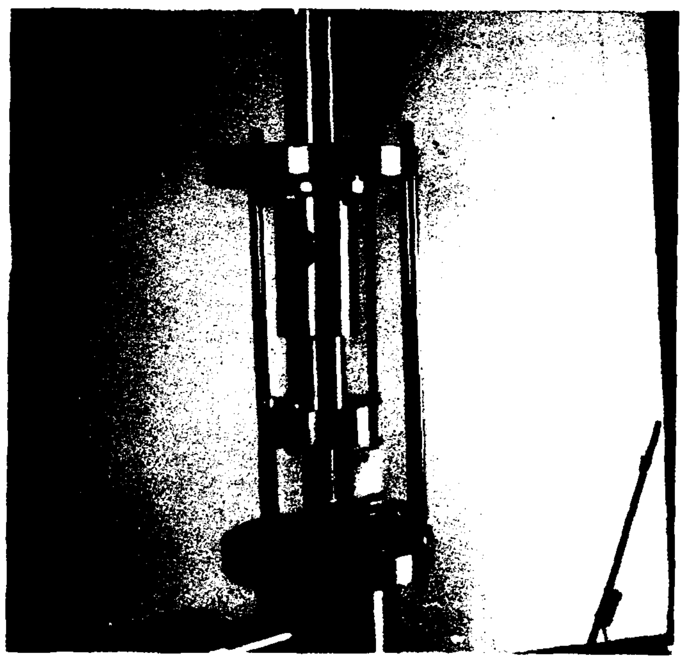


Figure 46 View of the Slip-Ring Brush Test Facility

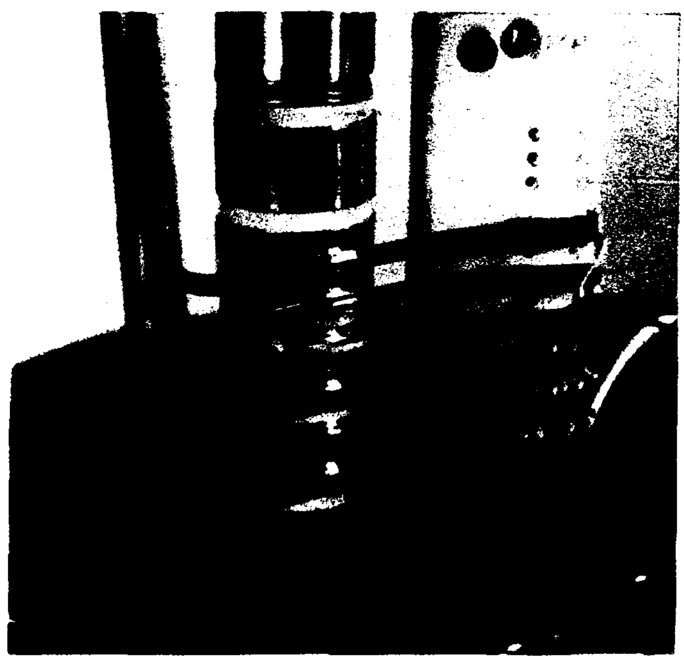


Figure 47 Close-up View of Brushes contacting Silver Plated Slip-Ring

The mean load on each brush was set to about 0.6N. Three pairs of brushes were tested simultaneously. A constant current supply was used to feed a current of 2 amps through each brush throughout the test, as shown in the schematic diagram in Figure 48. The slip-rings were rotated at 100 rpm for 10,000 revolutions, in vacuum at a pressure less than $1x10^{-6}$ torr. The voltage drop across a pair of brushes was monitored using a digital computing voltmeter, and used to calculate the contact resistance of that pair of brushes. The voltmeter was used to compute the maximum, minimum and mean voltage drops across pairs of brushes during 30 second periods, usually at intervals of 1,000 revolutions of the slip-rings, but more frequently at the start of each test. The brush dimensions were measured before and after each test, but the actual wear seen was too low to make meaningful assessments of the specific wear rates of the different types of material.

The measured resistances for each of the nine types of brush material, as a function of the number of slip-ring revolutions are shown in Figures 49-51. The general observations are:

- Increasing the amount of lead demonstrated an improvement in the performance in all cases.
- "HIP'ped" materials, (Figures 51A-C) produced low variations in the mean resistance throughout their tests and the superimposed peak resistances were only slightly greater. These brushes were the best compared to all others tested in this program.
- The 50/50 "As Cast" material gave a performance similar to the "HIP'ped" materials.
- The 75/25 and 50/50 "Shock Compacted" materials, and the 90/10 "As Cast" material, showed some variability in their mean resistances, and high peak resistances, during the early stages of their tests (up to one or two thousand revolutions of the slip-rings), but then behaved similar to the "HIP'ped" materials.

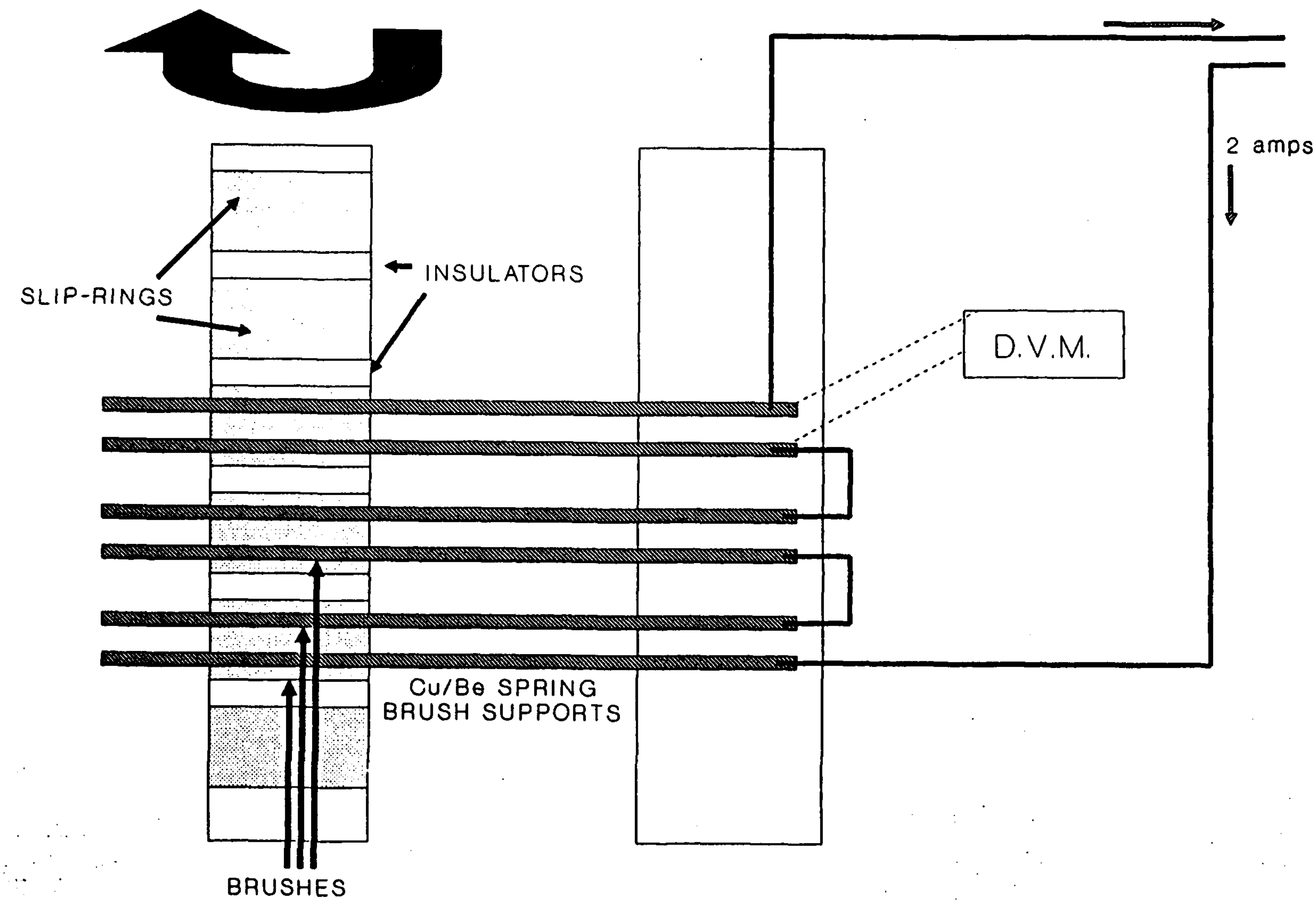


Figure 48 **Slip-Ring Rig: Schematic Layout during Brush Tests**

Figure 49-A
Brush Performance
50/50 As Cast Material

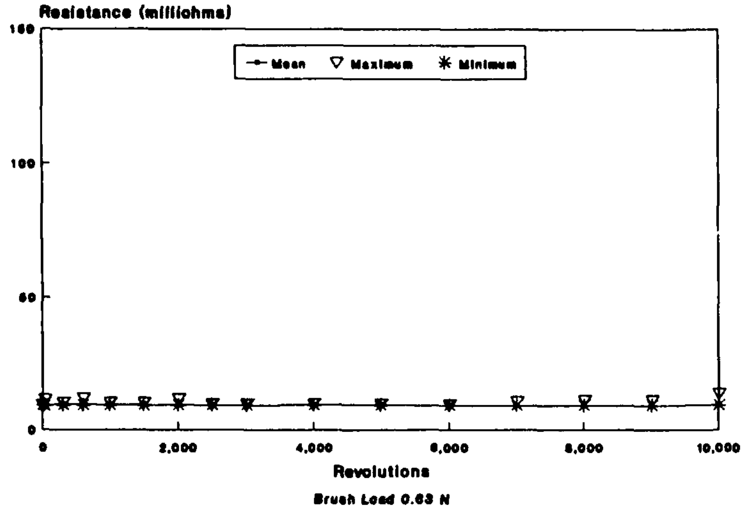


Figure 49-B
Brush Performance
75/25 As Cast Material

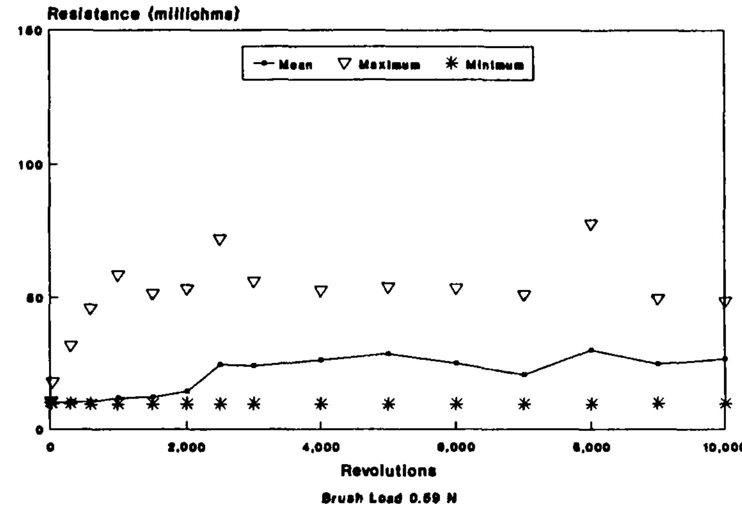


Figure 49-C
Brush Performance
90/10 As Cast Material

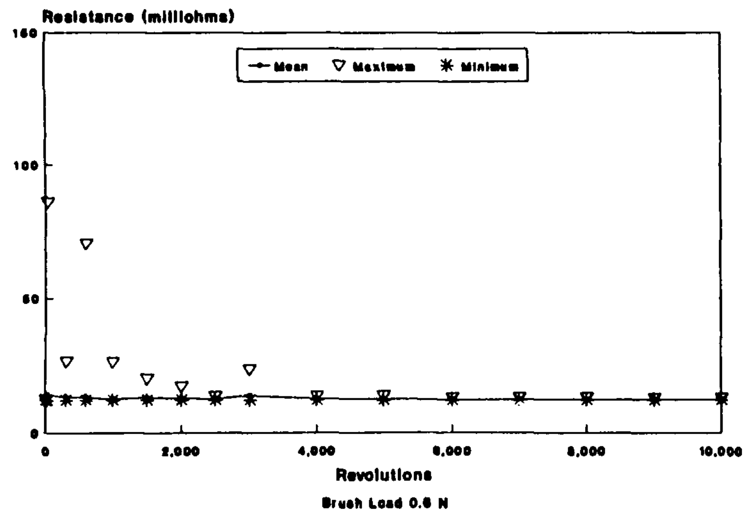


Figure 49 Brush Test Results of the "As Cast" Material

Figure 50-A
Brush Performance
50/50 -100+325 mesh Shock Compacted

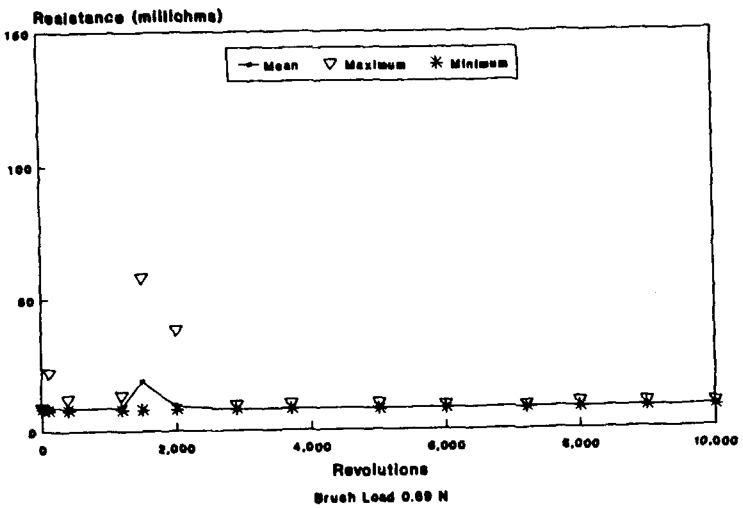


Figure 50-B
Brush Performance
75/25 -100+325 mesh Shock Compacted

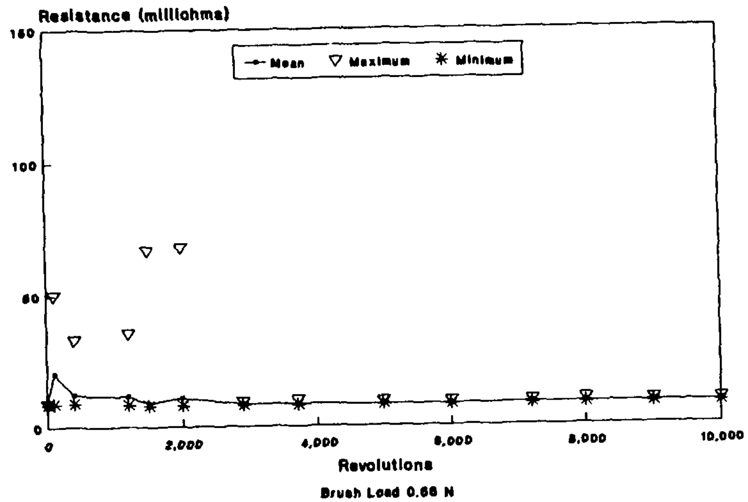


Figure 50-C
Brush Performance
90/10 -100+325 mesh Shock Compacted

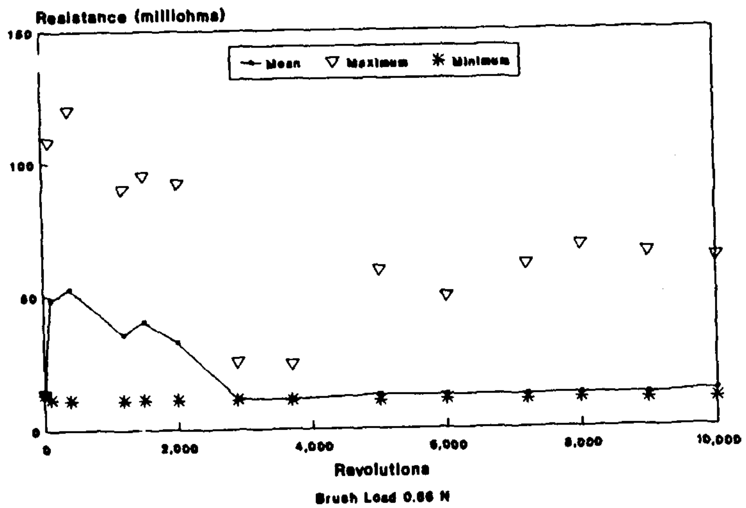


Figure 50 Brush Test Results of the "Shock Compacted" material

Figure 51-A
Brush Performance
50/50 -325 mesh HIPped Material

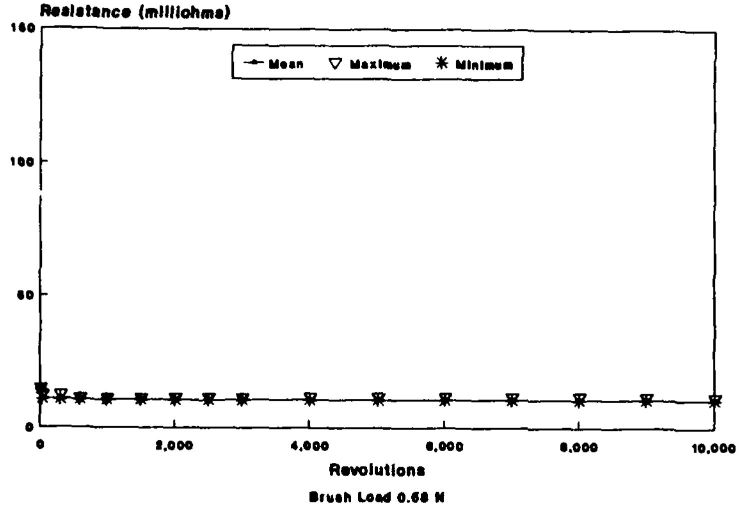


Figure 51-B
Brush Performance
75/25 -325 mesh HIPped Material

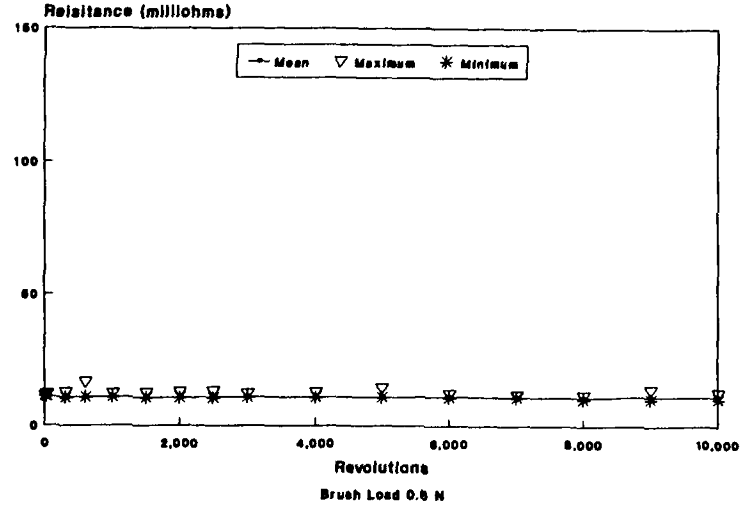


Figure 51-C
Brush Performance
90/10 -325 mesh HIPped Material

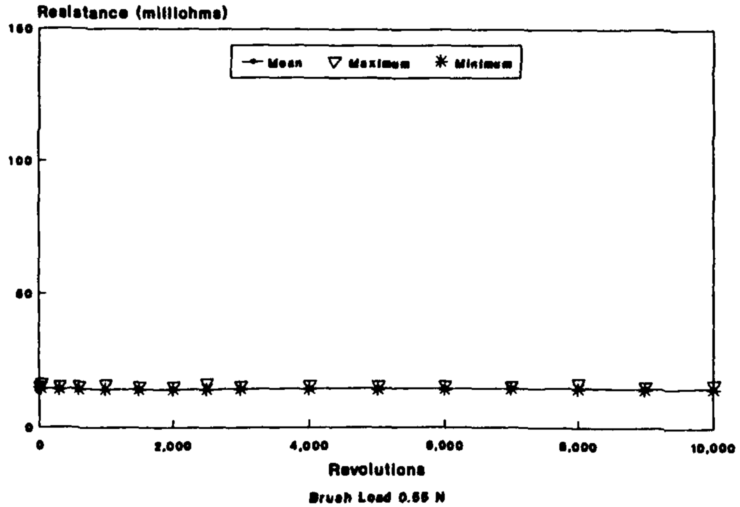


Figure 51 Brush Test Results of the "HIP'ped" material

- The 75/25 "As Cast", and the 90/10 "Shock Compacted" materials gave the worst performances, with high peak resistances, and the greatest variation in their mean resistances throughout the tests.

SEM examination of the brush condition after testing shows a large wear zone with ragged edges in the 90/10 -100+325 mesh "Shock Compacted" brushes (Figure 52). The observed wear zone is consistent with the noisy contact resistance observed throughout testing.

The 50/50 -325 mesh "HIP'ped" alloy brushes ran very quietly in terms of contact resistance throughout testing and this is consistent with the clean wear zone with no sign of raggedness in the contact area. These are representative of all the test samples, and provide pictorial evidence to support the test results (Figure 53). The "HIP'ped" materials were however all very successful, with low resistance variation throughout, comparing very favorably to the historical data both in terms of contact resistance level and variation.

However, this noticable improvement may not on its own be enough to generate further interest by the space community since the friction levels and high wear rates (as shown by the gear test results) may act as negative influences. If this market is to be addressed seriously, then a further extended period of testing varying speed and load would be required to show the limits of performance, and to allow proper wear rates to be measured on these specific items.

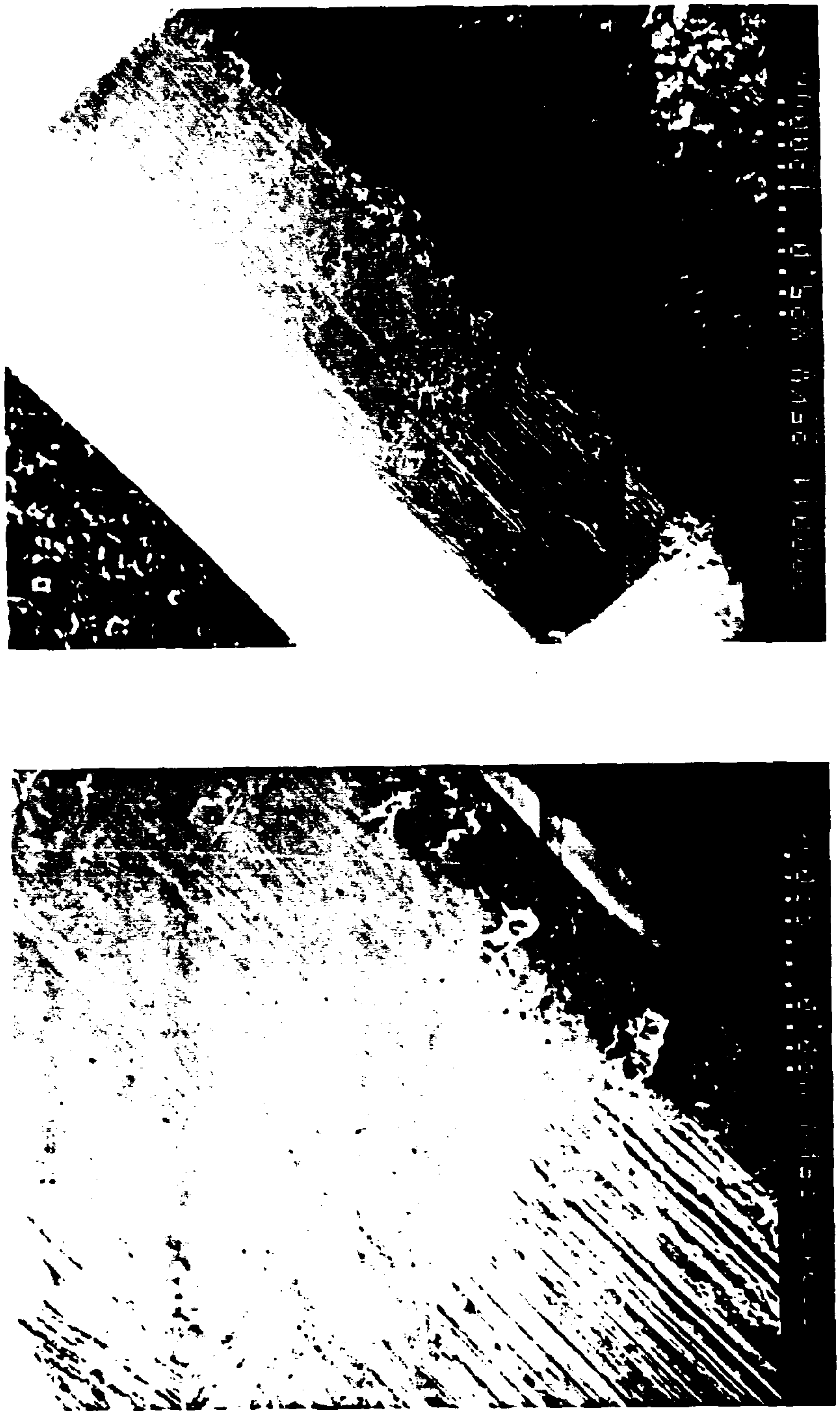
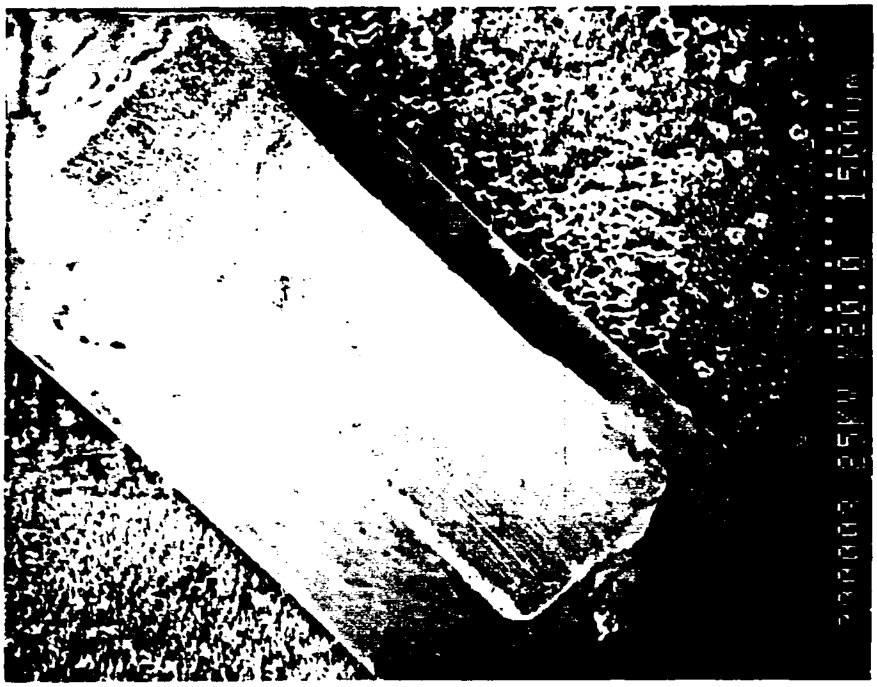


FIGURE 52 SEM Views of 90/10 -100 +325 Mesh Shock Compacted Brush after Testing



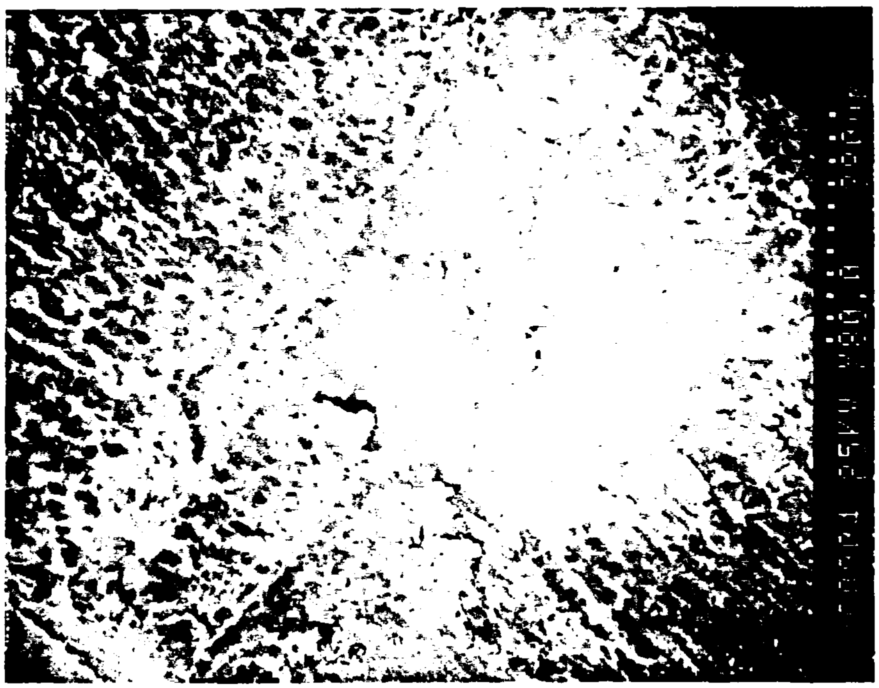


FIGURE 53 SEM Views of 50/50 -325 Mesh "HIP'ped" Brush after Testing

6. CONCLUSIONS

This program has demonstrated the following:

- Non-equilibrium compositions of copper lead alloys can be continuously cast into ingots or gas atomized into powders.

- The powders can be consolidated successfully using both "HIP'ped" and "Shock Compaction Methods."

- The "As Cast" and the "HIP'ped" powders can be readily machined into engineering components while the "Shock Compacted" materials proved to be brittle, and little prospect can be seen for this class of materials without further studies devoted to the optimization of heat treatment and compaction parameters to increase the strength and ductility of the base material.

The general conclusions from the friction and wear studies are the following:

- Processing and composition significantly influence the overall behavior of these alloys.

- It was clearly established that fine distributions of lead produced better friction and wear values than coarse distributions of lead.

- "As Cast" alloys showed low friction values but high wear rates. Clearly this suggests that lead distribution plays a major role in the film formation and degradation processes.

- "Shock Compacted" materials have to be post heat-treated to achieve ductility and reduce residual stresses induced by processing.

- The ability of lead to form a tenacious form of lead oxide during consolidation is probably responsible for the high friction values observed in the "HIP'ped" and "Shock Compacted" conditions.

The general conclusions from the testing of tribological components in vacuum suggest that:

- In the case of bearing cages, the best performance was provided by the 90/10 "HIP'ped" -325 mesh material, which far outperformed the standard lead bronze cages over the first one million revolutions, in that the torque noise of the running bearings was greatly reduced. Unfortunately beyond this point the performance suffered from unacceptable short-lived torque noise spikes as material was transferred to the bearing races from the cages.

- In the case of gears, the best performance was provided by the pair of gears manufactured from the 90/10 "HIP'ped" -325 material, however the wear rate was a factor of ten or more higher than other polymeric gears under similar conditions.

- In the case of bushings, the best performance was provided in the 50/50 alloy constituents. Long endurance at steady torque levels was recorded. The performance is very similar in terms of torque levels to the proprietary material Glacier DU, which is a sintered material. Commercial opportunities can exist for the -100+325 mesh material and will be purely dependent on the manufacturing costs.

- For brushes, the "HIP'ped" materials performed extremely well and the peak contact resistance remained stable near the mean levels throughout the test. The mean contact resistance was similar to that registered in earlier tests at NCT on the

standard pressed MoS_2/Cu/Si composite brushes, which also suffer from far higher peak resistance performance.

7.0. RECOMMENDATIONS FOR FURTHER WORK

This Phase II program has clearly identified several areas of promise for the application of copper-lead alloys. However, designers and materials engineers would be able to exploit the full potential for these alloys if the following areas are addressed in future work:

- Process optimization studies will be necessary in the case of hot isostatic pressing of the copper-lead powders. This will significantly improve the information available for pressing components at the correct temperature for each alloy composition.

- The "Shock Compacted" process demonstrated considerable promise and exhibited very fine microstructures in these alloys. However significant work related to post shock compaction processing to relieve the stresses will be required prior to fabrication of engineering components.

The testing of tribological components in vacuum has some areas which are worthy of consideration for further investigation. These include:

♦ Brushes are the most worthy of further consideration at this stage. A market for these powders in terrestrial applications relating to brush materials in car starter motors and other similar items, where copper lead powders are currently used is readily available. The brush industry currently blends individual copper and lead powders which leads to problems in homogeneity and environment. If free floating lead can be tied up as an alloy these powders can be used directly in brush applications.

- In the case of high value added brushes used in spacecraft, the following program of work would give the rest of the information required to prove their viability:-

  1) Measure friction levels and wear rates both in air and in vacuum against load and speed, when running against a silver plated hardened steel counterface.
  2) Perform further extended testing on the best materials in vacuum against silver plated slip rings.
  3) Fit a DC motor with sample brushes, and measure the "in-vacuo" performance characteristics.

  Each item of work should be performed sequentially to allow the best choices to be made at the end of each stage.

- With regard to the bearing cage performance, the "HIP'ped" material gave precisely the desired performance for the first period of running. Further work to enhance the "HIP'ping" parameters, or alternatively looking at different mesh sizes could lead to prolonging this behavior beyond the current result.

- The bushing market may be receptive to a new material both for terrestrial and space environments. Further development however will be dependent on the relative costs and performance of the powders versus the current standard materials.

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